Hard X-ray Observations of Cosmic-ray Accelerators

Yasunobu Uchiyama
with T. Tanaka & T. Takahashi (ISAS/JAXA)
for the Suzaku team
**X-ray Satellites**

**Chandra**
- Launch: 23 July 1999
- Vehicle: Space Shuttle
- Weight: 4.8 ton
- Spatial resolution: ~0.5"
- Point-source sensitivity: ~4e-15 erg/cm²/s (100 ksec)

**XMM-Newton**
- Launch: 10 Dec 1999
- Vehicle: Ariane 5
- Weight: 3.8 ton

**Suzaku**
- Launch: 10 July 2005
- Vehicle: M-V
- Weight: 1.7 ton

**INTEGRAL**
- Hard X-ray & Gamma-rays
- Launch: 10 July 2005
- Vehicle: M-V
- Weight: 1.7 ton
- Energy resolution: 7 eV (FWHM)
- Wide band: 0.2 -- 300 keV
Why X-ray?

Intimate connection between keV and TeV photons

(1) TeV gamma-rays require multi-TeV particles
(2) Multi-TeV electrons emit synchrotron X-rays

\[ h\nu_{\text{syn}} \approx 5 \left( \frac{B}{10\mu G} \right) \left( \frac{E_e}{100 \text{ TeV}} \right)^2 \text{ keV} \]

- Superb spatial resolution (<1") with Chandra
- Good sensitivities (< micro-Crab level)
- All-sky monitors (RXTE, Swift, Maxi in future)

PeV photons → Hard X-rays (This talk!)
Outline

- X-ray studies on Supernova Remnants (SNRs)
  - Results from ASCA & Chandra
- Suzaku X-ray satellite
- New results from Suzaku
  - TeV SNRs: RX J1713.7-3946 & Vela Jr.
  - unID HESS sources
- NeXT X-ray Satellite: to be launched ~2013
SNRs (1): The Remnant of SN 1006
“Anniversary”: Just 1000 years old

• This is the first evidence that forward shocks do accelerate electrons to “TeV” energies. (Koyama et al. 1995)

• Acceleration in “thin” filamentary structures (B-field amplification: Bell-Lucek hypothesis?)

Chandra X-ray
Long et al. 2003
Bamba et al. 2003

synchrotron X-rays

(This is called SNR G327.6+14.6)

Simple morphology probably because this SNR is far from Galactic Plane

Shell filled with TeV electrons

Interior is cool and thermalized

Figure 2.3: (left) X-ray photograph and (right) X-ray spectra of SN 1006 revealed by ASCA (after Koyama et al. 1995). Figures are provided by M. Ozaki.

Koyama et al. (1995)
SNRs (2) : Tycho’s SNR

the debris of supernova explosion in the year 1572

- reverse shock: synchrotron radio
- shocked ISM region is quite “narrow”
  \[ \frac{R_{\text{contact}}}{R_{\text{forward}}} = 0.93 \]

• This is thinner than a hydrodynamic expectation.
• Suggests modified dynamics due to efficient cosmic-ray (protons) acceleration

Hwang et al. 2002
Warren et al. 2005
SNRs (3): Non-thermal SNRs

ASCA revealed a remarkable class of SNRs

**RX J1713.7-3946**

**Vela Jr.**

ASCA X-ray

(Slane et al. 1999; Uchiyama et al. 2002)

- Only non-thermal (synchrotron) X-ray emission
- TeV Imaging shows a similar morphology (HESS)

Ideal targets for *Suzaku* and indeed the objects of this talk:

1. XIS 0.3-10 keV with 1’ resolution
2. HXD PIN 10-50 keV with 35’ aperture
Suzaku X-ray Satellite

God bird “Suzaku” from ancient myths

Japan 5th X-ray Satellite
Launched July 10, 2005
Instruments onboard *Suzaku*

**X-ray Mirror**

- X-ray telescope [XRT]
  - GSFC, Nagoya, ISAS/ISAS, TMU

- X-ray spectrometer [XRS]
  - GSFC, Wisconsin, ISAS/ISAS, TMU

- Extensible optical bench (deployed in orbit, f=4.5-4.75m)

**Hard X-ray Detector [HXD]**
- Tokyo, ISAS/JAXA, RIKEN, Saitama, Hiroshima, Kanazawa, ...

**X-ray Imaging Spectrometer [XIS]**
- Kyoto, Osaka, ISAS/JAXA, MIT, ...

**X-ray CCD camera**

5 units

4 units
Suzaku XIS (0.3-10 keV)

Low background (XIS, 0.3-10 keV)

Koyama et al. (in press)

Good energy response (< 1 keV)

Observed energy spectrum of SNR E0102.2-729

Suzaku XIS background is comparable to that of ASCA SIS.

Low instrumental background thanks to low Earth orbit
**Suzaku HXD (10 - 600 keV)**

Takahashi et al. (in press)

Compound-Eye Well-type Phoswich Detector

- **PIN** 10–60 keV (FOV 35' x 35')
- **GSO** 30–600 keV (FOV 4 deg x 4 deg)

Non-Imaging

**hard X-rays**
Suzaku HXD (10 - 600 keV)

Lowest background thanks to (BGO) active shields and narrow FOV

BGD

Kokubun et al. (in press)
Outline

- X-ray studies on Supernova Remnants (SNRs)
  - Results from ASCA & Chandra
- Suzaku X-ray satellite

  - New results from Suzaku
    - TeV SNRs: RX J1713.7-3946 & Vela Jr.
    - unID HESS sources

- NeXT X-ray Satellite:
Bright TeV SNR (1)
RX J1713.7-3946
SNR RX J1713.7-3946

HESS “TeV image”

contours:
ASCA X-ray (Uchiyama et al. 2002)
Broadband Spectrum

Synchrotron + Inverse-Compton

Advantages: similar morphology
Disadvantages:
- small B-field with large E_max
- TeV spectrum unmatched

Synchrotron + pion-decay

Advantages:
- a good fit to the spectrum
- energetically OK
Disadvantages:
- why morphology so similar?

From Horns’s talk

New keys: Suzaku hard X-ray (up to 50 keV) observations
Suzaku hard X-ray Observations

We have observed RX J1713.7-3946 in September 2006 with a total of 200 ks exposure. (Tanaka et al. in prep)

Suzaku XIS image (0.5 - 5 keV)

Suzaku HXD PIN (10-50 keV) measurements have been made in each 11 boxes (34′x34′).

Photon index (10-50 keV) for each box
Suzaku Wide band spectrum

Integrated over the entire remnant (energy range: 0.5 - 50 keV)

Interstellar absorption

power law

$E^{-\Gamma}$ with $\Gamma = 2.3$

Suzaku XIS+HXD spectrum 0.5 - 50 keV!! (high quality)

Spectral steepening > 5 keV
from a photon index $\Gamma = 2.3$
In the Sy+IC hypothesis, it is now possible to obtain physical parameters:

- Electron index = 1.9
- \( B = 10 \text{ uG} \)
- \( E_{\text{max}} = 100 \text{ TeV} \)

(similar to Aharonian et al. 2005)

**Bohm diffusion required**

- One-zone is OK? Yes (as shown later)
- B-field seems too low (c.f. Voelk et al. 2005)

**Synchrotron + IC Model**

(electron cooling taken into account)

To test this hypothesis, (1) GLAST measurements

(2) good statistics at \( \sim 100 \text{ TeV} (= E_{\text{max}}) \) to see *Klein-Nishina* suppression
keV-TeV Comparison

radial profiles

Suzaku vs HESS

pies 1-8 integrated:

consistent with the ASCA results
keV-TeV Surface Brightness Relation

- "keV excess" in NW and SW rims
- Compact features (like filaments) would account for the excess.

0.5' TeV imaging is needed to test this.
Bright TeV SNR (2)
Vela Jr. (RX J0852.0-4622)
Vela Jr. (RX J0852.0-4622)

young remnant of core-collapsed SN hidden in the old Vela SNR

ASCA X-ray (Slane et al. 2001)

Distance: uncertain 0.2 - 1 kpc

X-ray = Synchrotron
TeV = IC / pion-decay
**Suzaku hard X-ray Observations**

Only a “pilot” observation has been performed.

A power law up to 30 keV has been measured: \( \Gamma \approx 2.8 \)

We need mapping observations to conduct keV-TeV comparisons as we did for RX J1713.7-3946.

AO2 proposal (PI: Uchiyama)

HXD PIN: \( \sim \) sensitivity limits
Unidentified TeV Sources
Non-detection in X-rays favors "hadronic" origin of TeV gamma-rays (TeV IC without X-ray requires $B < a$ few uG)
The Japanese “NeXT” mission
Within about 10 years (Defined in ISAS’s Long Term Vision)

Venus Exploration 「PLANET-C」

Solar-powered Sail

Mercury Exploration 「BepiColombo/MMO」

VSOP2

First Hard X-ray Focusing with the finest X-ray spectrum

Finest resolution by Space VLBI
Based on the proposal 2005-Oct, Approved “Completion of pre-phase A” 
Waiting for the transition to Phase A/B

- **First Hard X-ray Focusing Observation**
  (10 - 80 keV)

- **Wide band observation** (0.3 - 300 keV) with high sensitivity

- **High Resolution (7 eV) X-ray spectroscopy**
  (0.3 - 10 keV) of diffuse sources
Hard X-ray Imaging

Multilayer Super Mirror: using Bragg reflection

Super Mirror + Hard X-ray Imager

Total Weight < 1700 kg
Large Area/Light Weight Mirror

with ASCA/Suzaku Style

Pt/C multilayer super mirror
(Nagoya U.)

<table>
<thead>
<tr>
<th>Mirror weight/telescope</th>
<th>Effective area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chandra</td>
<td>1500 kg</td>
</tr>
<tr>
<td>XMM</td>
<td>440 kg</td>
</tr>
<tr>
<td>Suzaku</td>
<td>20 kg</td>
</tr>
<tr>
<td>NeXT HXT</td>
<td>65 kg</td>
</tr>
</tbody>
</table>

![Graph showing the effective area of different telescopes as a function of energy (keV).](graph.png)
Breakthrough brought by Hard X-ray Focusing Telescope

Hard X-ray region is detector background dominated:

Rule of thumb
Detector Background $\propto$ Detector Volume

Focusing Telescope
Super Mirror (0.5-80 keV)

focal length 12 m

Hard X-ray Imager
Effective Area $\gg$ Detector Area

强有力的X射线成像

Effective Area = Detector Area

Collimator
Coded-Mask

Suzaku

NeXT

Integral/Swift
## Expected Performance

### baseline design

### For Hard X-ray Imager (HXT)

<table>
<thead>
<tr>
<th>Focal Plane</th>
<th>Hard X-ray Imager (HXI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>$&lt; 80$ keV</td>
</tr>
<tr>
<td>Effective Area</td>
<td>$\sim 300$ cm$^2$ at 30 keV</td>
</tr>
<tr>
<td>Imaging Quality</td>
<td>$\sim 60$ arcsec (HPD)</td>
</tr>
<tr>
<td>Effective FOV</td>
<td>$\sim 8$ arcmin</td>
</tr>
</tbody>
</table>

### For Soft X-ray Instruments (SXT)

<table>
<thead>
<tr>
<th>Focal Plane</th>
<th>Soft X-ray Spectroscopy/Imager</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>$&lt; 12$ keV</td>
</tr>
<tr>
<td>Effective Area</td>
<td>$\sim 500$ cm$^2$ at 30 keV</td>
</tr>
<tr>
<td>Imaging Quality</td>
<td>$\sim 60$ arcsec (HPD)</td>
</tr>
<tr>
<td>Effective FOV</td>
<td>$\sim 12$ arcmin</td>
</tr>
</tbody>
</table>
SGD (Soft Gamma-ray Detector)

New Concept:
Narrow Field of View Compton telescope

Compton kinematics inside the BGO WELL is the key to reduce the internal background

1. Select two-hits events
   (e.g. one in Si and one in CdTe)
2. Calculate the direction of “incident” gamma-ray by using Compton Eq.
3. Accept events only if the ring intercepts the FOV (0.5 deg for <100 keV, ~ 4 deg at 500 keV)

DSSD 0.5mm thick, 400 micron pitch 24 layers
CdTe Pixel Wall, 5-6 mm thick, 1-2 mm pitch
Conclusions

- **Suzaku** is suited for X-ray studies on TeV sources

- "**NeXT**" will realize the first **Hard X-ray Focusing Telescope** up to 100 keV (with 1' resolution)

- We hope the realization of TeV imaging with < 1' resolution to be compared with X-ray and hard X-ray images