New Insights into Cosmic-ray Acceleration in SNRs

Yasunobu Uchiyama (ISAS/JAXA)

mainly with F. Aharonian, T. Takahashi, T. Tanaka, K. Mori

Suzaku X-ray Universe (San Diego, Dec 2007)
Outline

• **Introduction**
  
  • Why do we care about Cosmic Rays (CRs) in SNRs?

• **X-ray Variability: “Seeing” Acceleration of Cosmic Rays!**
  
  • RX J1713.7-3946
  
  • Cassiopeia A

• **Suzaku x HESS**
  
  • (RX J1713.7-3946 in Tanaka’s talk)
  
  • Vela Jr *(preliminary)*
Introduction

Why we care CRs in SNRs

3 Major Objects in Very-High-Energies

1. Young SNRs
   SED: Sync + Pion-decay (proton) ?
   Engine: Supernova
   Dynamics: Non-relativistic ejecta

2. Pulsar Wind Nebulae
   SED: Sync + IC (electron)
   Engine: Rotating NS
   Dynamics: Relativistic wind

3. TeV Blazars
   SED: Sync + IC (electron)
   Engine: Supermassive BH
   Dynamics: Relativistic jet (beaming)
X-ray Variability (1) RX J1713.7-3946

Basic Information

Distance: ~ 1 kpc
Age: ~1600 yr
Radius: ~ 9 pc

Dominated by non-thermal X-ray
(Koyama et al. 1997, Slane et al. 1999)

TeV gamma-ray imaging by HESS

TeV ??
(1) leptonic
Inverse Compton

(2) hadronic
Pion decay

B-field is a key parameter.
X-ray Variability (1) RX J1713.7-3946

Basic Information (conti.)

- X-ray spectra: power-law type photon index 2.1-2.5 by ASCA and Chandra (Koyama et al. 1997; Slane et al. 1999; Uchiyama et al. 2003)
- Hard X-rays by RXTE (Pannuti et al. 2003)
- Synchrotron radiation by shock-accelerated multi-TeV electrons (Reynolds 1996)

Power-law Spectra (0.5 - 10 keV)

photon index $\Gamma \simeq 2.3$

$N_H \simeq 0.8 \times 10^{22} \text{ cm}^{-2}$

(almost) everywhere!

Uchiyama et al. (2003)
Most filaments (spatially extended) are variable in time!!

Timescale ~ 1 year

X-ray spectra: a power law with photon index ~2

Uchiyama et al. (2007)
X-ray Variability (1) RX J1713.7-3946

Variability Timescales

**Light crossing time**

\[ t_{lc} \sim 0.1 \left( \frac{\theta}{6 \text{ arcsec}} \right) \text{ year} \]

Variability timescale \( \Delta t_{\text{var}} \sim 10 \times t_{lc} \)

: impossible for non-relativistic plasma waves/motion

**Decaying = Synchrotron Cooling**

\[ t_{\text{sync}} \sim 1.5 \left( \frac{B}{\text{mG}} \right)^{-1.5} \left( \frac{\epsilon}{\text{keV}} \right)^{-0.5} \text{ year} \quad \rightarrow \quad B \sim 1 \text{ mG} \]

**Brightening = Acceleration of Fresh Electrons**

\[ t_{\text{acc}} \sim 1 \eta \left( \frac{B}{\text{mG}} \right)^{-1.5} \left( \frac{\epsilon}{\text{keV}} \right)^{0.5} \left( \frac{V_s}{3000 \text{ km s}^{-1}} \right)^{-2} \text{ years} \quad \rightarrow \quad B \sim 1 \text{ mG} \]

\[ \eta \sim 1 \]

Diffusive shock acceleration \( \eta \equiv \left( \frac{\delta B}{B} \right)^2 \)

“gyro-factor”

Consistent with Suzaku (Takahashi et al. 2008)
Suzaku Broadband Spectrum

RX J1713.7-3946

Takahashi et al. 2008

Uchiyama et al. 2007

Shock acceleration in the Bohm regime! $\eta \sim 1$

Spectral cutoff

Tanaka’s talk

★★ Spectral cutoff
★★ Shock acceleration in the Bohm regime! $\eta \sim 1$
X-ray Variability (1) RX J1713.7-3946

Combined with previous XMM data

- Synchrotron origin of X-rays is verified
- Variability: fast synchrotron cooling and fast CR acceleration
- B-field ~ 1 mG is necessary to account for the variability
Suzaku reveals hard filaments

Hard filaments are expected to be violently variable.

• We ask for monitoring observations (AO3, AO4,...):
  • twice a year, for ~4 years
• Filamentary regions: $B \sim 1 \text{ mG}$

• How about more diffuse regions? (Direct relation to TeV gamma-rays)

To account for:

Spectral shapes
Fluxes
Radio constraints

$\rightarrow$ • $B \sim 0.2 \text{ mG}$
Hadronic Origin of Gamma-rays

Average field of $B \sim 0.2$ mG $\longrightarrow$ IC (leptonic) unlikely

TeV has hadronic origin:
- Total proton energy: $W_p \sim 3 \times 10^{50} \, n^{-1} \, \text{ergs}$
- Proton roll off: $E_{p,\text{roll}} \sim 100 \, \text{TeV}$
- Electron cutoff: $E_{e,\text{cutoff}} \sim 10 \, \text{TeV}$

GLAST will determine proton index

Suzaku wide band
Tanaka’s talk for details
X-ray Variability (2) Cassiopeia A

Basic Information

“Spitzer + Hubble + Chandra” view of the youngest known SNR in our Galaxy

Distance: 3.4 kpc
Age: 340 yr
Radius: 2.5 pc

Forward shock (synchrotron x-ray)

Reverse shock (synchrotron radio/IR/x-ray)
X-ray Variability (2) Cassiopeia A

X-ray Image and Spectrum

Chandra (Hwang et al. 2004)

Si-K  Fe-K  4-6 keV

Suzaku XIS+PIN spectrum
(Data from Y. Maeda)

Tentative decomposition into T/NT

nonthermal cutoff power law

thermal brems.

Both T/NT: Reverse-shock dominated

What is the origin of nonthermal X-ray?
2000, 2002, 2004 data have almost identical ACIS settings: aim point, roll angle, etc.

Hwang et al. (2004)

Time evolution over 4 yrs
brightening and decaying
spatially extended (few arcsecs)
X-ray Variability (2) Cassiopeia A

Sequence of Chandra Images

Uchiyama et al.

Si-K band

4 - 6 keV

Similar to variable components found by Patnaude & Fesen (2007)

Si-K: silent

4-6 keV: violent

synchrotron origin
X-ray Variability (2) Cassiopeia A

Spectra of Variable Filaments

Uchiyama et al.

Synchrotron radiation from reverse-shocked ejecta
KeV excess in NW = Variable filaments
CR acceleration in this region would have become active in recent years.
(Tanaka’s talk)
Suzaku vs HESS (2): Vela Jr  *(Preliminary)*

**Basic Characters**

- **ASCA** (Slane et al. 2001)

- **Distance:** 0.2 ~ 1 kpc (uncertain)
- **Age:** ? yr
- **X-ray = nonthermal dominated**
  - (Slane et al. 2001)  $\Gamma \simeq 2.7$

- **HESS imaging**

  - **Largest TeV object in the sky**
  - (Aharonian et al. 2005)
Suzaku vs HESS (2) : Vela Jr  *(Preliminary)*

Suzaku Mapping Uncovered 3 Components!

Northern hemisphere 10 ks x 18 pointings (AO 2)

**Low**
- Suzaku 0.3-0.7 keV (Old Vela)

**Medium**
- Suzaku 1-1.5 keV (Vela Jr. thermal?)
  - Region 1
  - Region 2
  - Region 3

**High**
- Suzaku 3-5.7 keV (Vela Jr. Nonthermal)

- HESS
Suzaku vs HESS (2) : Vela Jr (Preliminary)

Suzaku Mapping Uncovered 3 Components!

If confirmed, we will get a robust estimate of CR proton energetics based on Suzaku-HESS comparison:

\[ W_p \sim 3 \times 10^{50} \, n^{-1} \, \text{ergs} \quad \text{(for } D = 1 \, \text{kpc}) \]
End Remarks

6 things we uncovered in this year

- **Presence of X-ray Variability**
  decaying = synchrotron cooling
  brightening = CR acceleration (and B-field amplification)

- **Evidence for synchrotron origin of X-ray emission**
  synchrotron origin of X-ray emission is verified (especially in Cas A)

- **Evidence for B-field amplification**
  B ~ 1 mG amplified by CR themselves (in forward and reverse shocks)

- **Evidence for Hadronic origin of TeV gamma-rays**
  TeV gamma-rays are hadronic (especially in RX J1713.7-3946)

- **PeV acceleration**
  CRs can be accelerated to PeV energies, given B~mG and gyro-factor~1.

- **Presence of Thermal X-rays in Vela Jr** *(preliminary)*
  We will get a robust estimate of proton contents.
X-ray Variability

Summary

- **Variability**
  decaying = synchrotron cooling
  brightening = CR acceleration (and B-field amplification)

- **Synchrotron origin**
  synchrotron origin of X-ray emission is verified (especially in Cas A)

- **Witnessing CR acceleration**
  “real time” observations of CR acceleration processes

- **B-field amplification**
  B ~ 1 mG amplified by CR themselves (in forward and reverse shocks)

- **Hadronic TeV gamma-rays**
  TeV gamma-rays are hadronic (especially in RX J1713.7-3946)

- **PeV acceleration**
  CRs can be accelerated to PeV energies, given B~mG and gyro-factor~1.