Particle Acceleration in SNRs

Yasunobu Uchiyama (ISAS/JAXA)

with
Felix Aharonian (DIAS,MPIK)
Takaaki Tanaka (SLAC)
Tadayuki Takahashi (ISAS/JAXA)
**Collisionless Shock**

Shocks do exist. No doubt.

But, Coulomb collisions do not occur on this scale.

At shocks, energy transfer is mediated by some MHD/plasma waves.

"collisionless shock"

Cosmic ray production

Tycho’s SNR (exploded in AD 1572)

Chandra X-ray image

Diameter: 8 arcmin
**Introduction**

**Collisionless Shock**

---

**Classical View of “collisionless shock”**

**Thermal ions**
- Maxwellian distribution: $kT_i$

**Thermal electrons**
- Maxwellian distribution: $kT_e$

$\Rightarrow$ ?

**Fermi Acceleration**
- (e.g. Bell, Blandford)

**Cosmic Rays**
- Power law distribution:
  - total energy
  - max/min energy
  - number index

$kT_i > kT_e$

_in young SNRs_
**Modern View of “collisionless shock”**

**Thermal ions**
- Maxwellian distribution: \( kT_i \)
- \( kT_i > kT_e \) in young SNRs

**Thermal electrons**
- Maxwellian distribution: \( kT_e \)

**Fermi Acceleration**
- (e.g. Bell, Blandford)
- CR back pressure (?) (e.g. Ellision)

**Cosmic Rays**
- Power law distribution:
  - total energy
  - max/min energy
  - number index

---

**Introduction**

**Collisionless Shock**
Indirect Arguments for CR-modified Dynamics

Tycho’s SNR

Very thin layer of shocked ISM (7% of the radius) indicates a large compression factor.

CR-modified dynamics? Warren+05

SNR E0102-72 (in SMC)

* Expansion velocity 6000 km/s predicts $kTi \sim 45$ keV (RH relation)
* Measured $kTe \sim 0.7$ keV predicts $kTi < 45$ keV (Coulomb heating)

CR-modified dynamics? (CRs lowered $kTi$) Hughes+00
### Indirect Arguments for CR-modified Dynamics

**XEUS** will provide a “direct” test by measuring thermal Doppler broadening, thus ... $kT_i$

Combined with expansion measurements ($V$), and $kT_e$.

**XEUS** specifications:

* EA: OK!
* spectral resolution: OK!
* angular resolution: 2” preferable

---

**SNR E0102-72 (in SMC)**

- Expansion velocity 6000 km/s predicts $kT_i \sim 45$ keV (RH relation)
- Measured $kT_e \sim 0.7$ keV predicts $kT_i < 45$ keV (Coulomb heating)

**CR-modified dynamics?**

(CRs lowered $kT_i$)  

Hughes+00
Modern View of “collisionless shock”

**Thermal ions**
Maxwellian distribution: \( kT_i \)

**Thermal electrons**
Maxwellian distribution: \( kT_e \)

\( kT_i > kT_e \) in young SNRs

**Fermi Acceleration**
(e.g. Bell, Blandford)

**Cosmic Rays**
Power law distribution:
- total energy
- max/min energy
- number index

CR back pressure (e.g. Ellision)
Introduction

Collisionless Shock

Post-Chandra View of “collisionless shock”

Thermal ions
Maxwellian distribution: $kT_i$

Thermal electrons
Maxwellian distribution: $kT_e$

$kT_i > kT_e$
in young SNRs

Fermi Acceleration
(e.g. Bell, Blandford)
CR back pressure (?)
(e.g. Ellision)

Cosmic Rays
Power law distribution:
total energy
max/min energy
number index

Bell hypothesis

Magnetic Fields
total energy
max/min scale
index (e.g. Kolmogolov)

Calculation from “first principle”: not available
We need Experiments/Observations!!
Case Study (1)

SNR RX J1713.7-3946 (age 1600 yr)

The brightest diffuse TeV emitter in the sky
RX J1713.7-3946 (age 1600 yr)

SNR RX J1713.7-3946

HESS (color)
ASCA (contours)

10-100 TeV electrons

TeV gamma-ray imaging by HESS

Direct evidence of 10-100 TeV particles

Origin of TeV gamma-rays:
hadronic (pion-decay) or leptonic (IC) ?
RX J1713.7-3946

Our Chandra Monitoring Observations

Most filaments (spatially extended) are variable in time!!

Timescale $\sim 1$ year

Decaying

X-ray spectra:
a power law with photon index $\sim 2$

Brightening and Decaying

Chandra (color)
HESS (contours)

Witnessing Acceleration of Cosmic Rays!!

Uchiyama et al. (2007)
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

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

Brightening = Acceleration of Fresh Electrons

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

\[ \eta \sim 1 \]

Consistent with Suzaku

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

“gyro-factor”
Why B-field so Strong?

Shock compression of ISM: B ~ 5 uG is not enough.

- **Magnetic field generation at shocks**
  - Non-linear amplification of B-field by CRs themselves
  - "Bell-Lucek hypothesis"
    - Bell & Lucek 2001
    - Bell 2004

  Amplification factor of ~ 100

- **Other evidence for strong B-fields in SNRs**
  1. Thin X-ray filaments (Vink & Laming 2003; Bamba+03,05): > 0.1 mG
  2. Absence of TeV gamma-rays in SN 1006: > 0.1 mG
  3. Cas A SED: > 0.4 mG (Atoyan+ 2000) (note: RT instability)
RX J1713.7-3946

Wide-band X-ray Spectroscopy with Suzaku

Southwest rim

Tanaka PhD thesis 2007
Uchiyama et al. 2007
Takahashi et al. 2008

- Spectral cutoff (we see it for the first time in SNRs)

Fermi acceleration theory: \( \varepsilon_{\text{cutoff}} \sim 2 \left( \frac{V}{2000 \text{ km s}^{-1}} \right)^2 \eta^{-1} \text{ keV} \)

- Shock acceleration in the Bohm regime! \( \eta \sim 1 \)
Hadronic Origin of Gamma-rays

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

TeV has hadronic origin:

- Total proton energy: \( W_p \sim 3 \times 10^{50} n^{-1} \) ergs
- Proton roll off: \( E_p \sim 200 \) TeV
- Electron cutoff: \( E_e \sim 20 \) TeV

GLAST will determine proton index

\( W_p \sim 3 \times 10^{50} n^{-1} \) ergs

\( E_p \sim 200 \) TeV

\( E_e \sim 20 \) TeV
Hadronic Origin of Gamma-rays

Average field of B ≈ 0.2 mG; IC (hadronic) unlikely

Suzaku wide band: TeV has hadronic origin:

\[ W_p \sim 3 \times 10^{50} \, n^{-1} \, \text{ergs} \]

GLAST will determine proton index

proton roll off \[ E_p \sim 200 \, \text{TeV} \]

\[ E_p > \text{electron cutoff} \]

\[ E_e \sim 20 \, \text{TeV} \]
• **Maximum Energy of CRs:** Lagage-Cesarsky limit

$$E_{\text{max}} \sim 1.2 \left( \frac{R}{9 \text{ pc}} \right) \left( \frac{V}{3000 \text{ km s}^{-1}} \right) \left( \frac{B}{0.1 \text{mG}} \right) \eta^{-1} \text{ PeV}$$

**HESS spectrum of RXJ1713.7-3946**

$$E_p \sim 200 \text{ TeV} : \text{CR-modified shock?}$$

(see Ellison+08)
Case Study (2)

SNR Cassiopeia A (age 340 yr)

The youngest Galactic SNR
**Cassiopeia A (age 330 yr)**

**Chandra X-ray**
- Shock-heated ejecta
  - $kT_e \sim 1-2$ keV
- Shock-accelerated electrons
  - If $B \sim 0.1$ mG, $E \sim 10$ TeV (both forward/reverse shocks)

**Spitzer 3.6um**
- Accelerated electrons in ejecta
  - If $B \sim 1$ mG, $E \sim$ GeV (radio), TeV (IR)

**VLA Radio**

**Ennis et al. 2007**

**MAGIC**
- TeV gamma-rays

**Accelerated particles**
- $E \sim 10$ TeV
(1) line emissions from ionized heavy ions
ionization degrees: $kTe$ & $nt$ (density x elapsed time)

(2) thermal bremsstrahlung from shock-heated electrons
$kTe \ll kTi$  non-equilibrium temperature

(3) synchrotron radiation by shock-accelerated electrons
$E = 10$ TeV in $B = 1$ mG radiates X-rays
Cassiopeia A the Movie


Si line (1.7-2.2 keV)
thermal X-ray emission from shock-heated ejecta
(1) SE quadrant: large-scale dimming by 2%/yr
(2) A few compact knots brightening  

4 yr interval (age 330 yr)
Uchiyama & Aharonian
submitted to ApJL

(see also Patnaude & Fesen 2007)
Cassiopeia A the Movie


Continuum (4-6 keV)
- thermal bremsstrahlung from shock-heated ejecta
- + synchrotron component
- many knots/filaments brightening/decaying 10%/yr

4 yr interval (age 330 yr)

Uchiyama & Aharonian
submitted to ApJL
Cassiopeia A

Year-scale Variability in Synchrotron Radiation

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

4 - 6 keV images
Cassiopeia A

Spectra of Variable Filaments

Flux changes

Index changes

brightening accompanies hardening

X-ray spectra are consistent with a synchrotron model

\[ \Gamma \approx 2.3 \]
Cassiopeia A

Variability Timescales

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

  - Evidence of synchrotron x-ray emission at internal shocks  
  - Evidence of shock-acceleration at internal shocks

**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**

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

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

“gyro-factor”

Consistent with Atoyan’s Model
GLAST will measure the shape of CR hadron spectrum:
(1) proton-proton collisions in forward shocked regions, or
(2) oxygen-oxygen collisions in reverse shocked regions.

(Future NeXT mission will detect nonthermal bremsstrahlung.)
<table>
<thead>
<tr>
<th></th>
<th>Cas A reverse shock</th>
<th>RXJ1713 forward shock</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>thermal</td>
<td>50</td>
<td>N/A</td>
<td>$10^{49}$ erg</td>
</tr>
<tr>
<td>CR p</td>
<td>1 (pp)</td>
<td>30/n</td>
<td>$10^{49}$ erg</td>
</tr>
<tr>
<td>CR e</td>
<td>0.2</td>
<td>0.003</td>
<td>$10^{49}$ erg</td>
</tr>
<tr>
<td>B</td>
<td>0.7</td>
<td>2</td>
<td>$10^{49}$ erg</td>
</tr>
<tr>
<td>Emax (p)</td>
<td>&gt;100</td>
<td>200</td>
<td>TeV</td>
</tr>
<tr>
<td>Emax (e)</td>
<td>20</td>
<td>20</td>
<td>TeV</td>
</tr>
</tbody>
</table>
XEUS Specifications in light of this talk

* EA of m^2-scale: fine!
* spectral resolution of a few eV: fine!
* FoV of arcmin^2: acceptable
* angular resolution: 2” preferable
* mission life time: > 5 yr preferable (for monitoring)
* wide-band spectroscopy: up to 40 keV preferable
* polarimeter: very welcome
End Remarks

Summary

• **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

• **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

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