Observational Clues of Galactic Cosmic Rays

in X-ray point of view

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0. 1. Galactic cosmic rays

SNR as Galactic cosmic ray accelerator
- enough energy, heavy elements
- sync. X-rays, gamma-rays from MeV to TeV

Remaining Problems

(1) Injection from thermal to nonthermal

(2) what determine $E_{\text{max}}$
how to accelerate particles up to which energy?

(3) escape from acc. region
to be cosmic rays p? e$^+$e$^-$?
0.2. How to get information?

- **X-ray:**
  - synchrotron from e
  - thermal emission
  - info. on accelerated e
  - info. on density, kT, ...

- **gamma-ray:**
  - IC emission from e
  - emission from pi-on
  - info. on accelerated e/p

**X-ray observations are important to know accelerated particles and background plasma!**
0.3. Recent and near future X-ray observatories

Chandra
excellent spatial resolution
filament structure, time evolution ...

XMM-Newton
large effective area
spectroscopy of faint sources

Suzaku
low background, wideband detector
detection of faint and extended sources

NuStar
imaging at 10-80 keV
good for hard sources (FOV is small)
ASTRO-H (planned to launch 2015)
- excellent spectral resolution for extended sources
- wideband spectroscopy from 0.2-600 keV
- imaging capability in 10-80 keV

we have (and will have) a lot of useful information with present and near future X-ray missions
1. Injection
from thermal plasma to nonthermal particles
1.1. How to observe the injected energy from thermal plasma to high energy particles

From Rankine Hugoniot relation

- Efficient particle acceleration steal energy from the thermal energy of downstream plasma
- We need excellent spectral resolution to measure ion kT
Injection efficiency measured from ion kT
obs. of ejecta knots in SNRs
-> Doppler shift + thermal broad

In the case of Puppus A Oxygen
Doppler v ~ 1500km/s
expected O kT ~ 130 keV
<-> observed O kT < 30 keV
(XMM RGS; Katsuda+13)
due to non-equilibrium? or energy injection? (Katsuda+13)
In the case of non ionization equilibrium effect, the ratio of $kT$ increase following the mass of elements.

In the case of injection, the ratio of $kT$ follows the TIGER result or same among elements?

-> *It should be determined with ASTRO-H!*

excellent E resolution for diffuse sources
large effective area in wide X-ray band

-> determine the ratio of $kT$ for several elements

-> measure the E injection?
1.2. Environment of cosmic ray acceleration

Why only a part of SNRs have synchrotron X-rays?
Is there any environment of shocks for easier acceleration?

Key target: RCW86

position dependence of thermal and nonthermal X-rays

regions w. bright thermal X-rays has smaller photon index ??

Some clue of efficient particle acceleration site (Tsubone+, in prep.)
Non-thermal X-ray dominated SNRs

Bright TeV SNRs have no significant thermal X-rays
thermal X-ray luminosity $\sim n_e^2$ -> background plasma is thin ??
pulsar candidate -> core-collapsed SNRs ?
expanding in low density cavity ?
2. Acceleration mechanism from wide band spectrum
2.1. Change of CR spectrum

w. various acc. efficiency or escape parameters

CR spectrum: 

\[ N(E) \propto E^{-p} \exp \left[ - \left( \frac{E}{E_{\text{max}}},e \right)^a \right] \]

only 3 parameters! 

- \( p \): photon index
- \( a \): cutoff shape
- \( E_{\text{max}} \): maximum energy of particles

\( p \): test particle case: \( \rightarrow p=2 \)

w. efficient synchrotron cooling: \( p=3 \) at \( E_{\text{max}}>E \) 

\( \text{(Longair84)} \)

\( \leftrightarrow \) Tycho, Cas A: \( p>2 \)? (Abdo+10)

\( a \): depend on what determine \( E_{\text{max}} \)

- \( a=\beta+1 \) in cooling limit (Yamazaki+13)
- \( a=2\beta \) in age limit (Kang+09)
- \( a=\beta \) in escape limit (Ptuskin+05, Yamazaki+13)

\( \beta \): diffusion coefficient \( K(E) \sim E^\beta \)
How to determine \( p \), \( a \), and \( E_{\text{max}} \)?

CR: \[ N(E) \propto E^{-p} \exp\left[ -(E/E_{\text{max}})^a \right] \]

synchrotron emission with magnetic field

for \( p \):
- power-law with \( s = (p-1)/2 \)
- below cut-off
- radio obs. will determine \( p \)

for \( a \) and \( E_{\text{max}} \):
- slow slope around X-ray band

We need wide band E coverage to determine \( a \) and \( E_{\text{max}} \)

-> Nustar / ASTRO-H!
Photon index comparison in various parameters

Wide band obs. will enable us to distinguish what makes the cut off

(Yamazaki+14)
better sensitivity
-> better distinction
of models

\[ R_I = \frac{F(10-30 \text{ keV})}{F(30-80 \text{ keV})} \]

(Yamazaki+14)
Photon index comparison in various parameters

RXJ 1713-3946
(Suzaku: Tanaka+08)
p is not determined (no radio obs.)

week B (week sync. cooling): failed
(Katz & Waxman08)
a>2, beta>1 (Bohm limit !)

strong B (strong sync. cooling):
(Yamazaki+14)
Photon index comparison in various parameters

We need more samples with Nustar / ASTRO-H!

Cas A
(Suzaku: Maeda+09)

No theoretical line!!
Not one-zone??
hard X-rays are not sync.?? (Vink08)
(3) escape from acc. region to be cosmic rays
3.1. escape from shocks of SNRs

Particles have to escape from SNRs to be cosmic rays!
- SNRs detected with Fermi has the cutoff $E$ of $\sim 10$ GeV
- The most famous accelerator, RXJ1713 (age $\sim 2000$ yrs) has cutoff around TeV (Aharonian+07)

$\Rightarrow$

High $E$ particles are already escaped?

(Funk 11)
Non-thermal X-ray luminosity starts to decrease within ~100 yrs

(Nakamura+12)

(already escaped/cooled ??)
Excellent example: NE shell of W28

TeV emission from MC escaping particles?

Colliding w. MC! (OH mesar)

Thermal X-ray knots -> lap time from collision to escape?? (XMM could not measure the age of the plasma)

GeV+TeV from shocked MC softer particle escaping?

ASTRO-H will show us the time scale of escape
Old SNR + TeV gamma-rays

HESS J1745-303: TeV unID source

X-rays: no excess in continuum nearby old SNR

excess of neutral iron line -> dense matter irradiated by particles or photons

particles escaping from the SNR to be cosmic rays ??
3.2. $e^+e^-$ escape from pulsar wind nebulae

Pulsars and Pulsar wind nebulae: possible cosmic ray origin for $e^+$ and $e^-$?
leptons loose their energy during propagation, but nearby sources can contribute.

Young Pulsars and Pulsar wind nebulae: very bright synchrotron emission -> strong B
particles loose their energy quickly

sync. loss time scale:

$$2 \left( \frac{B}{10 \mu G} \right)^{-3/2} \left( \frac{\epsilon_{\text{syn}}}{1 \text{ keV}} \right)^{-1/2} \text{ kyr.}$$
Suzaku discovered extended nebulae around middle-aged pulsars

low bgd of Suzaku/XIS -> faint and extended emission!

PSR J1420−6048 and Rabbit (Kishishita+12)

HESS J1825-137

HESS J1356-645

(Uchiyama+09)

(Izawa+, in prep.)

age of system = pulsar age $t_c$

-> time evolution of PWNe
Time evolution of PWNe

PWNe keep expansion at >> 2kyr !!

particle escape from the PWN system ??
magnetic turbulence dumping ?? (Bamba+10)
Or, just sampling effect ??

PWNe can brighten when reverse shock hit them (Gelfand+09)

The “evolution” discovered with Suzaku may just see “the PWNe hit by reverse shock recently” (reverberation phase; Bandiera+13)

How to judge these models ??

We need samples with SNR thermal plasma information. In order to make the hit on $10^{5-6}$ years, we need SNRs in very thin ISM region
New observational result to distinguish models

**HESS J1536-645:**
New PWN w. \( t_c = 7.3 \) kyr

thermal X-rays
  from the center
\(-\) SNR emission
density \( \sim 0.6 \) cm\(^{-3}\)

\(-\) too old and too dense
  for reverse shock
  to hit the PWN!
  (Izawa+, in prep.)

We may witness the \( e^+e^- \) escape
  from PWN systems
4. Summary

- X-ray observations are essential to study the emission from accelerated particles and background plasma.

- The injection rate, what determine the maximum $E$, and escaping from acc. system will be addressed with latest and near-future X-ray missions.