Recent Progress on Supernova Remnants
- Progenitors, Evolution, Cosmic-ray Acceleration -

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1.1. Role of supernova remnants in the universe

**Thermal aspects:**
- Thin plasma with $kT \sim $ keV
- Time scale $< \sim 10^4$ yrs
- In non-equilibrium

**Nonthermal aspects:**
- Shock $v \sim 10^{3-4}$ km/s
- Accelerate particles efficiently
- Distribute cosmic rays

**Origin:**
- Explosion of light (Ia) and heavy (cc) stars
- Distribute thermal/kinetic $E$
- Compact stars

SNRs makes the diversity of the universe!
1.2. Many unresolved problems

Thermal aspects:
- thin plasma with $kT \sim \text{keV}$
- time scale $\sim 10^5$ yrs in non-equilibrium

Origin:
- explosion of light (Ia) stars
- heavy (cc) stars

Nonthermal aspects:
- shock $v \sim 10^{3-4}$ km/s accelerate particles efficiently

2. How amount elements?
How do they mix into ISM?
Plasma condition?

1. Diversity of each class
- Are Ia really universal?
- Which cc makes NS/BH?

3. How to escape to be cosmic rays?

We will introduce the recent progress on these topics.
1. Diversity of progenitor explosion
2.1. Types of Supernova remnants

**Type Ia**
End-point of mass accretion to WD or up to $M_{\text{ch}}$ (SD) WD-WD merger (DD)
A lot of Fe, Ni, Cr, Mn
Isotropic explosion?
“Standard candle”

**Core-collapsed (CC)**
End-point of heavy stars ($>\sim 10 \, M_\odot$)
A lot of lighter elements O, Ne, Mg, Si, S, ...
Neutron stars, black holes

Questions:
Can we distinguish Ia/cc for SNRs with X-ray observations?
Do they have diversity more than types?
SD/DD progenitor mass of CCs?
2.2. Type estimation from X-ray morphology (Lopez+11)

Ia: isotropic explosion
cc: anisotropic explosion

Lopez+11: wavelet analysis of Chandra image of many SNRs

CC SNRs has more distorted morphology!
**NuSTAR: $^{44}$Ti enables us to access unheated ejecta**

**CC SNR expansion with $^{44}$Ti**

**SN 1987A (~30 yrs)**

- Only red-shift $^{44}$Ti line
- $\sim 700$ km s$^{-1}$
- Asym. distribution
- Neither isotropic nor axial symmetric expansion

**Cas A (~330 yrs)**

- Shocked Si/Mg, Fe (Chandra)
- $^{44}$Ti (NuSTAR) (Grefenstette+14)
- Asym. distribution

**CC SNRs show highly asymmetric expansion**
Does Ia expand isotopically?

**SN1006** (Uchida+13)

Si, S, Fe are abundant in south eastern region

**Tycho** (Yamaguchi+17)

pure iron ejecta (no Cr, Mn)

Several “text-book” Ia remnants show anisotropy.
It is still an open issue how isotropic Ia explosions are.

important on heavy element distribution in the universe, maximum luminosity of SNe (amount of Ni), etc.
2.3. Type estimation from Iron K line center (Yamaguchi+14)

low density medium for Ia
high density (CSM or ISM) for cc

Ia has lower E iron-K
Ia is really in the low density ISM

More classification from spectral info.?
2.4. Origin of Ia?

~$M_{\text{ch}}$, dense core ($\rho \geq 2\times 10^8 \text{ g/cm}^3$)

high $\rho$ in SD core makes more Ni, Mn
due to more electron capture

3C397 needs $M_{\text{ch}}$

Strong diagnostics to distinguish SD and DD
Related to abundance of CGs
We need calorimeter to resolve Ni from Fe forest

Perseus cluster
Hitomi/SXS
(Hitomi coll. 16)

Athena / XARM will identify many Ia SNRs to be SD or DD.
2.5. Variety of CC SNRs

Cas A  
NASA/CXC/SAO
bright thermal  
faint NS

G11.2-0.3  
NASA/CXC/Eureka Scientific/Roberts+
both thermal/PSR

Crab nebula  
NASA/CXC/SAO
only bright pulsar/PWN

What makes such difference?

Crab Thermal line search  
with Calorimeter onboard Hitomi
-> very tight upper-limit  
plasma mass < 1Mo
-> electron capture SN?
2.6. Where are SNRs with BHs?
Not yet, but we have several SNRs with a HMXB.

SXP 1062 in the SMC
(Hénault-Brunet+12)

HMXB: $P=1062$ s, maybe neutron star
SNR: too old to see in X-rays ($r=20$ pc)

CXOUJ053600.0-673507 in DEML241

HMXB with O5III(f) star (Seward+12)
the most luminous gamma-ray binary (Corbet+16)
abundance pattern -> progenitor $> 20$ Mo
(Bamba+06)

Can we find first SNR w. BH ??
2. Topics on thermal plasma
2.1. Plasma in SNRs are highly non-equilibrium!

- Density $\sim \text{cm}^{-3}$
- Time scale $\sim 10^{3-4}$ yrs
- Non-equilibrium

situation is not simple
- Recombining plasma
- Rapid cooling
- Ionizing plasma

Understanding the plasma condition is the starting point of thermal aspects of SNRs.
2.2. First firm detection of recombining plasma in SNR

Suzaku spectrum of IC443 (Yamaguchi+09)
middle-aged SNR, interaction with molecular cloud

Plasma in IC443 underwent rapid cooling.
2.3. What is the origin of recombining plasma?

Recombining plasma SNR list:
IC443 (Yamaguchi+09), W49B (Ozawa+09), G359.1-0.5 (Ohnishi+11),
W28 (Sawada+12), W44 (Uchida+12), G346.6-0.2 (Yamauchi+13),
3C391 (Sato+14)  Okon, Matsumura, talks in parallel session

All middle-aged, interaction with dense clouds

Origin of rapid cooling?

- rapid expansion in low density medium
- thermal conduction with cold molecular clouds
- energy injection to particle acceleration
Key target: G166.0+4.3 (Matsumura+17)

East:
small radius interaction?

Discovery of RP component

West:
large radius low density?

Non-detection of RP

Recombining condition happens due to interaction?
More samples/studies needed.
3. Topics on particle acceleration
3.1. Are really shocks of SNRs Galactic Cosmic-ray accelerators?

When SNRs are young ....

thin & time variable synch. X-ray filaments
-> amplified magnetic field

GeV - VHE gamma-rays
-> TeV particles

-> efficient particle accelerators
When SNRs become older (~2000 yrs old) ...

no sync. X-rays
only GeV gamma-rays with cut-off \(\sim 10\) GeV

(Acero+16)

Acc. particles escape from the acc. sites?

(Funk11)
More clue of particle escape

VHE gamma-ray image of RX J1713-3946 (H.E.S.S.+16)

exposure: 163 hour!

CTA will resolve more. (Nakamori+17)
3.2. What makes particle escape?

Amplified magnetic field does not allow particle to escape.

-> Need magnetic field dumping
  - interaction with molecular cloud? (Ohira+12)
  -> similar origin to recombining plasma

RP SNR lists:
  IC443 (Yamaguchi+09), W49B (Ozawa+09), G359.1-0.5 (Ohnishi+11),
  W28 (Sawada+12), W44 (Uchida+12), G346.6-0.2 (Yamauchi+13), 3C391 (Sato+14),
  G166.0+4.3 (Matsumura+17)

GeV source, VHE gamma-ray source

most of RP SNRs are gamma-ray emitters

Interaction with molecular clouds makes
both recombining plasma
  particle escape

Thermal info. on escape site environment!
4. Summary

- Supernova remnants make diversity of the universe in thermal and nonthermal aspects.
- We can resolve Type of progenitor SNe.
- Both Ia and CC have variety.
- Plasma condition in SNRs are more complicated than previous understanding.
- We now see the clue of particle escape to be cosmic rays, and we need to understand what makes escape.
- Plasma condition on the escape site may have a key of escape.