X-ray Observations of Supernova Remnants

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High energy emission of young supernova remnants

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Young supernova remnants : Chandra large programs

Tycho (SN 1572)
Type Ia

Cas A
Core collapse

Young supernova remnants:

- Chandra large programs
- ~330 yr

Tycho (SN 1572)
- Type Ia
- ~330 yr
- D ~ 2.0 - 4.5 kpc
- 8 arcmin
- Warren et al. 05

Cas A
- Core collapse
- ~330 yr
- D ~ 3.3-3.7 kpc
- 5 arcmin
- Hwang et al. 04

(References: Krause et al. 08, Ruiz-Lapuente 04, Schwarz et al. 95, Smith et al. 91, Kirshner et al. 87, Albinson et al. 86, De Vaucouleurs 85, Reed et al. 95)
Braking of the electron in a magnetic field

X-ray synchrotron

accelerated e^-

from radio to X-rays

In reverse Compton effect

γ-rays

Proton – proton collision

γ-rays

Talk by Lemoine-Goumard

accelerated p

ambient medium p

neutrino

μ

p

π^0

π^+/

e^-/e^+

γ-rays
Synchrotron-dominated supernova remnants

Maurin et al. in prep
SN 1006
Acero et al. 09
G347.3-0.5
Aschenbach et al. 99
RX J0852.0-4622
(Vela Jr)

30 arcmin
1 degree
2 degrees
1.3 arcmin

Vink et al. 06
RCW 86
XMM-Newton

Park et al. 09
G330.2+1.0

G1.9+0.3
Reynolds et al. 09

Chandra
Objective: to understand the process of particle acceleration and the origin of Galactic cosmic rays

- What is the level of magnetic field amplification at the shock?
- What is the maximum energy of the accelerated particles?
- What is the efficiency of particle acceleration?
- …

Why are X-rays crucial to investigate particle acceleration?

- Physics of the synchrotron emission of the electrons accelerated at the highest energy
- Physics of the thermal gas
  - Global parameters of the remnant: \( \Rightarrow \) downstream density \( \Rightarrow \) ambient density
  - Back-reaction of accelerated ions (protons)
- Capability of performing spatially-resolved spectroscopy at small scale (< 10 arcsec)
How large is the magnetic field? Is it very turbulent? Is it amplified?

The magnetic field is a crucial parameter:
- for understanding particle acceleration
- for deriving the maximum energy of accelerated particles
- for interpreting the origin of TeV $\gamma$-rays: leptonic versus hadronic

Morphology and variability of the synchrotron emission
- Sharp filaments observed at the forward shock: width determined by synchrotron losses of ultrarelativistic electrons
  (Park et al. 09, Parizot et al. 06, Bamba 05, 04, 03, Vink & Laming 03, …)
- Fast variability of the brightness of these filaments
  (Patnaude et al. 09, Uchiyama et al. 08, 07)
- Broad band modeling of the nonthermal emission
  (Berezhko et al. 09, Voelk et al. 08, …)

=> high value of $B_{\text{downstream}}$ (~ 50-500 $\mu$G) which implies large magnetic field amplification

Patnaude et al. 09
Maximum energy of electrons and protons

What is the maximum energy of accelerated particles?
Electrons are a few % of cosmic rays but can reveal a lot on the mechanism of
diffusive shock acceleration
⇒ accelerated like protons, except for the radiative losses

Spectrum of the synchrotron emission (radio + X-rays)

• Measurement of the rolloff photon energy $h\nu_{\text{roll}}$, observable in X-rays
• Estimate of downstream magnetic field

⇒ Estimate of the maximum energy of accelerated electrons:
$$E_{\text{max}} = 39 \left(\frac{h\nu_{\text{roll}}}{B_{10}}\right)^{1/2} \text{TeV} \sim \text{few 10 TeV}$$

G1.9+0.3: the youngest observed galactic SNR
(Reynolds et al. 08, 09, Green et al. 08)

Expansion by 16 % between 1985 and 2007
⇒ \(V_s \sim 14000 \text{ km/s for } D \sim 8.5 \text{ kpc, age } \sim 100 \text{ yr}\)

\(h\nu_{\text{roll}} \sim 2.2 \text{ keV}, \text{ among the highest reported}\)
$$E_{\text{max}} \sim 70 \text{ TeV assuming } B \sim 10 \mu\text{G}$$

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How does $E_{\text{max}}$ and hence particle acceleration vary with B orientation?

High latitude SNRs evolving in a uniform interstellar magnetic field, like SN 1006, offer the possibility to investigate this dependence.

**Spatially resolved spectroscopy of the synchrotron emission**

⇒ Measurement of the azimuthal variation of $\nu_{\text{roll}}$ along the SNR shock

**SN 1006**: very strong variations (h$\nu_{\text{roll}}$ up to 5 keV), which cannot be explained by variations of the magnetic compression alone.

⇒ Maximum energy of accelerated particles must be higher at the bright limbs than elsewhere.
Efficiency of particle acceleration

What fraction of the shock energy can be tapped by the cosmic rays?
Evidence for ion acceleration in SNRs?
NL diffusive shock acceleration

- Curvature of the particle spectra (Berezhko & Ellison 99, Ellison & Reynolds 91, ...)
- Lower post-shock temperature (Ellison et al. 00, Decourchelle et al. 00)
- Shrinking of the post-shock region (Decourchelle et al. 00)

Curvature of the spectrum: indications in a few SNRs

- **SN 1006**: combining radio and X-ray data
  (Allen et al. 08)
- **RCW 86**: combining radio and X-ray data
  (Vink et al. 06)
- **Cas A**: from infrared data
  (Jones et al. 03)
- **Tycho and Kepler**: from radio data
  (Reynolds & Ellison 92)
If efficient ion diffusive shock acceleration

- larger compression ratio
- lower post-shock temperature
  than for test-particle case
  (Chevalier 83, Ellison et al. 00, Decourchelle et al. 00)

Indication of strong back reaction in young SNRs

- **1E0102**: post-shock electron temperature from X-rays and shock velocity from X-ray proper motion
  (Hughes et al. 00)
- **RCW 86**: post-shock proton temperature from H$\alpha$ broad line and shock velocity from X-ray proper motion
  (Helder et al. 09)

No back-reaction in the older SNR

- **Cygnus Loop**: post-shock electron temperature from X-rays and shock velocity from optical proper motion
  (Salvesen et al. 09)

50 % post-shock pressure in relativistic particles
  (Helder et al. 09)
If efficient ion diffusive shock acceleration modified hydrodynamics
=> narrower shocked region than test-particle case
(Decourchelle et al. 00, Chevalier 83)

Indication of strong back reaction in young SNRs
• Cas A: X-ray proper motion and morphology (Patnaude et al. 09)
• SN 1006: morphology (Miceli et al. 09, Cassam-Chenaï et al. 08)
• Tycho: morphology (Warren et al. 05, Decourchelle et al. 04)
Shock heating of the ejecta and ambient medium by the forward shock

Collisionally excited atom

Atomic deexcitation

X-ray bremsstrahlung

Braking of the electron in an electric field

Saclay Irfu Supernova Remnants and Pulsar Wind Nebulae in the Chandra Era, Boston, July 2009
Thermal emission from the shocked ambient medium

Access to the global properties of the remnant
- ambient medium: density, composition
- supernova: shock velocity and radius \(\Rightarrow\) age, SN energy and ejected mass
- shock physics: particle acceleration (Spitkovski), collision-less e⁻ and ion heating (Laming)

Shock physics
- **High post-shock oxygen temperature** in SN 1006 (XMM-Newton/RGS, Vink et al. 03)
  \[kT_O \approx 528 \pm 150 \text{ keV} \quad \text{and} \quad kT_e \approx 1.5 \text{ keV} \Rightarrow \text{small degree (5\%) of e⁻/ion equilibration at the shock}\]

Low density ambient medium for
- the SN Ia remnants:
  - G330.2+1.0: \(n_0 \approx 0.1 \text{ cm}^{-3}\), Park et al. 09
  - SNR 0509-67.5 \(n_0 < 0.6 \text{ cm}^{-3}\), Kosenko et al. 08
  - Tycho: \(n_0 < 0.6 \text{ cm}^{-3}\), Cassam-Chenaï et al. 07
  - SN 1006: \(n_0 < 0.05 \text{ cm}^{-3}\), Acero et al. 07
- **the core collapse remnant** RXJ1713.7-3946: \(n_0 < 0.02 \text{ cm}^{-3}\), Cassam-Chenaï et al. 04b
  \(\Rightarrow\) impact the level of pion decay emission in the TeV range due to proton-proton collisions

- **Stellar wind environment** for the core collapse SNR Cas A: proper motion and morphology, Patnaude et al. 09

- **Sub-solar abundances in the Magellanic clouds** (Borkowski et al. 06, 07, …)
Thermal emission from the shocked ejecta

Access to the elements synthesized by the supernovae => keys to the determination of the SN type of the remnant

A new class of Type Ia supernova?

- **Dense Fe-rich ejecta** in DEM L238 and DEM L249 in the LMC
  ⇒ substantial amounts of CSM? Remnant of prompt Type Ia SN with young progenitors? (Borkowski et al. 06)

- **Kepler’s SNR**: iron emission, absence of oxygen and optical evidence of CSM.
  ⇒ SN Ia explosion in a more massive progenitor? (Reynolds et al. 07)

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**Chandra**

DEM L238

~ 10000 yr

Optical

Kepler

~ 400 yr

512 ks

Borkowski et al. 06

Reynolds et al. 07

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Thermal emission from the shocked ejecta

Presence of Cr and Mn Kα lines in the X-ray spectrum of young SNRs

- W49 B (ASCA, Hwang et al. 00, XMM-Newton Miceli et al. 06)
- Tycho (Suzaku, Tamagawa et al. 09)
- Cas A, Kepler (Cr only, Chandra, Yang et al. 09)

⇒ For type Ia, Mn / Cr is a promising tracer of progenitor metallicity (Badenes et al. 08, 09)
⇒ cf Badenes’s talk

Z = 0.048
Thermal emission from the shocked ejecta

Access to the repartition and kinematics of the synthesized elements
- understanding of SN explosion (asymmetry, level of mixing of elemental layers)
- level of mixing with the ambient medium (chemical enrichment in galaxies)

Highly non-uniform distribution of thermodynamic conditions => asymmetric SN explosion? (Park et al. 07)

Highly non-uniform distribution of element => spatial inversion of a significant portion of the SN core (Hughes et al. 00)

Fesen et al. 2006

Hwang et al. 2004
What is the kinematics of the ejecta?

Bulk motion of the ejecta through Doppler shift measurements

=> deep insight in the expansion of the ejecta and explosion mechanism through asymmetries and inversion of the nucleosynthesis product layers.

- **Tycho**: 2800-3250 km/s for the shell of iron-emitting ejecta (Suzaku, Furuzawa et al. 09)

- **Puppis A**: fast-moving oxygen knots at -3400 and -1700 km/s (Katsuda et al. 08)

- **Cas A**: from -2500 to +4000 km/s (Chandra/HETG, Lazendic et al. 06, XMM-Newton, Willingale et al. 01; Chandra, Hwang et al. 01)

Si-K, S-K and Fe-K Doppler maps

20" x 20" images, Willingale et al. 02
Radioactive decay of 44Ti

Desintegration of radioactive nuclei in the ejecta

\[ \beta^- \text{ decay} \]

\[ \gamma \text{-ray lines} \]

\[ \beta^+ \text{ decay} \]

\[ \gamma \text{-ray lines} \]

\[ e^+/e^- \text{ annihilation} \]

\[ \nu \text{ : neutrino} \]

\[ e^+ : \text{positron} \]

\[ e^- : \text{electron} \]

\[ Z : \text{proton number} \]

\[ N : \text{neutron number} \]
Radioactive decay in supernova remnants: $^{44}\text{Ti}$

Access to the total mass of $^{44}\text{Ti}$ synthesized by the supernovae

$\Rightarrow$ keys to the very depths of SNe and to the physical conditions of the explosion

**Decay-chain by electronic capture:**

$^{44}\text{Ti} \ (85 \text{ yr}) \rightarrow ^{44}\text{Sc} \ (5.6 \text{ h}) \rightarrow ^{44}\text{Ca}$

$\Rightarrow$ 3 $\gamma$-ray lines (detected in Cas A)

- 67.9 and 78.4 keV (BeppoSAX, Vink et al. 01, INTEGRAL, Renaud et al. 06)
  $\Rightarrow$ $M(^{44}\text{Ti}) = 1.6 \times 10^{-4} \ M_{\odot}$ in Cas A

- 1157 keV (Comptel, Iyudin et al. 94) + search with INTEGRAL/SPI (Martin et al. 09)

$\Rightarrow$ X-ray $K_{\alpha}$ lines of $^{44}\text{Sc}$ at 4.1 keV due to K-shell vacancies (Leising et al. 01)

- Claim of a possible detection in RX J0852.0-4622 (ASCA, XMM-Newton, Chandra) but infirmed by Suzaku (Hiraga et al. 09)

Difficult task with current hard X-ray instruments
$\Rightarrow$ NuSTAR (Simbol-X currently cancelled)
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Supernova remnant

Particule acceleration at the shock
- Magnetic braking
- X-ray synchrotron
- Inverse Compton effect

Heating of the ejecta by the reverse shock

Heating of the ambient medium by the forward shock

Desintegration of radioactive nuclei in the ejecta
- \( Z : \) proton number
- \( N : \) neutron number

Proton-proton collision
- \( e^+e^- \) (electron/positron)
- \( \nu \) (neutrino)
- \( \gamma \) (gamma rays)

Graphic design by Aurélie Bordenave - Cea 2009

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Summary

X-rays are providing a wealth of in-depth results on supernova remnants which are providing relevant answers to prime astrophysical issues:

- Particles acceleration, magnetic field and the origin of Galactic cosmic rays
- Heating and chemical enrichment of galaxies
- Supernova explosion physics and standard candles for cosmology
- ...

Strength of current X-ray observatories:

- Spatially resolved spectroscopy at small spatial scale
- High resolution spectroscopy

⇒ Needs for large programs to get sufficient statistics at the spatial, spectral and temporal scales relevant to the processes at work in SNRs.
⇒ Needs for mission extension of the current X-ray observatories as long as they give satisfaction, pending and preparing the future international X-ray observatory IXO.