Supernovae remnants

Anne Decourchelle
Department of Astrophysics- UMR AIM
CEA Paris-Saclay

20th anniversary of the launch of XMM-Newton
Supernovae remnants in X-rays:

- Shocked ejecta heated to millions degrees emit X-rays
- X-ray synchrotron from electrons accelerated at the shock to TeV energies
INTRODUCTION

Observing in X-rays supernovae remnants tells us about

- Supernovae explosion mechanism
- Nucleosynthesis, driving chemical enrichment
- Progenitor and SN environment (stellar wind, molecular clouds, superbubbles,..)
- Particle acceleration, contributing to the Galactic Cosmic rays
- Shocks physics, magnetic field amplification
- Injection of energy and turbulence in the ISM
Nucleosynthesis of the elements in the Universe

- In stars during their lifetime: hydrostatic nucleosynthesis ⇒ long timescale, classic onion-skin structure
- In supernovae: explosive nucleosynthesis ⇒ very short timescale (s) and large energy (kinetic ~ $10^{51}$ ergs)
  ⇒ most of heavy elements from Si to Fe peak, and heavier elements

⇒ SNe are the effective mechanism for producing and dispersing the synthesized element in the ISM

Supernovae:
- Thermonuclear explosion: SN Ia
  main provider of Fe (~75 %) and Fe peak nuclei
- Gravitational core collapse for stars > 8 Msol
  main provider of intermediate elements (Si-Ca): 70 %
**Nucleosynthesis in SN Ia: Tycho (SN 1572) supernova remnant**

**SN Ia explosion mechanism**: Tycho’s X-ray spectrum favours a delayed detonation model (Badenes et al. 06)

**Elemental distribution in the ejecta**
- **radial stratification** of the elements (Fe inside)
- **anisotropies** in the distribution of Fe-rich and Si-K/Ca-rich ejecta

**Presence of rare elements: Ti, Cr and Mn**
- Well correlated to Fe K
- Indications of Ti line emission (at >2 sigmas)

Fe-peak nuclei seem to be spatially co-located in the remnant, in agreement with the predictions of Type Ia SN models.

---

**20th anniversary of the launch of XMM-Newton**
SN 1006: SN Ia
a detailed characterization of the plasma properties

Spatially resolved spectroscopy analysis

XMM-Newton 3 color images
(RED: 0.3–1 keV; GREEN: 1–2 keV; BLUE: 2–8 keV)

30 arcmin diameter

XMM-Newton global spectrum of SN1006

Li et al. MNRAS 2015

Tessellated meshes overlaid on the 0.3–8 keV:
3596 regions, each containing $\geq 10^4$ counts from
the combination of MOS-1, MOS-2, and PN
SN1006: SNIa
deep insight into the properties of the thermal plasma

Properties of the thermal non equilibrium plasma:

- characterize the average thermal and ionization states of such an extended source
- the gas spans a large range of hydrodynamical evolutionary stages.

Li et al. MNRAS 2015

Probability distribution functions

20th anniversary of the launch of XMM-Newton
583 tessellated regions dominated by thermal emission

- Abundance pattern in the ejecta consistent with typical Type Ia SN products.
- Spatial distribution of heavy elements (Fe) supports an asymmetric explosion
- Asymmetric environment

- asymmetric explosion of the progenitor star.
- Non uniformity of the metal distribution
- abundances pattern indicate a progenitor mass of about 15 Msolar.

Tsunemi et al. 2007

Levenson et al. 97

20th anniversary of the launch of XMM-Newton
Mature remnants: Cygnus Loop
RGS observations of the southwestern knot

- High Forbidden-to-resonance Line Ratio of O VII discovered in the Cygnus Loop
  - Charge exchange contribution enhanced around dense shock-cloud interaction (post-shock ions/neutral gas)
  - Confirmation of low abundances (0.2-0.4 solar)

Dynamics of X-ray-emitting ejecta in the oxygen-rich CC SNR Puppis A

- Dynamics of the X-ray emitting ejecta oxygen knot
- Thermodynamic properties ($kT_e$, $kT_O$)
- Shock physics

Method: EPIC + RGS observations

3 color image: 0.5–0.7 keV (red), 0.7–1.2 keV (green), and 1.2–5.0 keV (blue)

Katsuda et al. 2013
Dynamics of X-ray-emitting ejecta in the oxygen-rich CC SNR Puppis A

Katsuda et al. 2013

- **Prominent K-shell lines**, including O VII Heα forbidden and resonance, O VIII Lyα, O VIII Lyβ, and Ne IX Heα resonance,

- **Line centroids blueshifted** by ~ 1480 km s⁻¹ fully consistent with that of the optical Ω filament.

- Line broadening of O VIII Lyα < 0.9 eV, indicating an oxygen temperature of 30 keV, 10 times lower than the O knot in SN1006 (Broersen et al. 1013)

- EPIC: kTe ~ 0.8 keV and ionization timescale of ~ 2 × 10¹⁰ cm⁻³ s

=> ejecta knot was heated by a collisionless shock of ~ 600–1200 km s⁻¹ and subsequently equilibrated due to Coulomb interactions
Population studies: SNRs in the LMC

First homogeneous catalogue of the X-ray spectral properties of SNRs (51) in the LMC (Maggi et al. 2016)

=> Clues to progenitor types (13% exhibits Fe K lines, 39% supernova ejecta)

⇒ ISM abundances (O, Ne, Mg, Si, Fe) ~ 0.2-0.5 solar

⇒ Ratio of SN CC/SN Ia ~ 1.35 over last few 10^4 years
Non-thermal dominated SNRs: RXJ1713-3946

- Hydrodynamical and broadband modelling to constrain the SNR origin and nature of particle acceleration

Ellison et al. 2012
Non-thermal dominated SNRs: RXJ1713-3946

Proper motion between 13 yr
=> Velocity measurement
~ 3500 km/s

Age ~1500-2500 yrs

Acero et al. 2017

Acero, in prep
Non-thermal dominated SNRs: first detection of thermal emission


Softness map (0.5–1.5keV/1.5–8keV) plus contours as X-ray surface brightness.

Model B (OFF1) in linear scale

Relative abundances of Ne, Mg, Si and Fe

=> progenitor mass of about 20 Msun

=> result of SN Ib/c from a close binary system in which binary interactions removed a massive hydrogen envelope.
Conclusions

A large tribute of XMM-Newton to the study of supernova remnants

- key contribution for the spatially resolved spectroscopy of SNRs: acceleration properties, thermal plasma, kinematics
- key contribution for source population studies in the LMC

-nucleosynthesis, particle acceleration, shock physics, shock interaction with the ISM-

- very rich scientific exploitation
- in synergy with other observatories in X-rays with Chandra, Suzaku, in gamma-rays, optical, infrared, ..
- with modelling and theory

Large programs are key to perform ambitious studies
Prepare the path to Athena Observatory