Probing the properties of extragalactic SNRs

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X-RAYS: newly formed SNRs
Thermal emission from the material behind the shock front ($T > 10^6$ K) or/and non-thermal emission from relativistic electrons
(e.g. review by Vink 2012)

OPTICAL: sign of older SNRs
Cooling region behind the shock front ($T \sim 10^5$ K)

RADIO: throughout the life of a remnant
Around the shock or behind it

Different wavelengths depict different evolutionary stages in the life of a remnant
The (derived) properties of SNRs depend on:

- Environment/ISM (density, temperature)
- Progenitor properties (stellar wind density, mass loss rate, composition)
- Age / Evolutionary stage of the SNR
- Selection effects

The details of this connection are poorly understood.

Importance of multi-wavelength studies on SNRs
The (derived) properties of SNRs depend on:

- Environment/ISM (density, temperature)
- (multi-wavelength properties)
- Progenitor properties (e.g. X-ray spectra from the ejecta of young SNRs)
- Age / Evolutionary stage of the SNR (Toy model)
- Selection effects (e.g. easier to detect optical SNRs in low density/diffuse emission regions)
- A multi-λ study is essential

Importance of multi-wavelength studies on SNRs
MW SNRs: Pros and Cons

Census of Galactic SNRs: 294 (Green 2014)

Physics from individual remnants - interaction with ISM

However, they are severely hampered by

Galactic absorption
(SNRs are almost exclusively in the galactic plane-most can only be studied at radio)

distance uncertainties
(crucial properties cannot be estimated; e.g. size, luminosities)

Difficulties in probing their evolution and performing systematic studies
Extragalactic SNRs: Pros and Cons

- At the same distance
- Internal Galactic absorption effects are minimized (especially on face-on galaxies)
- Observing SNRs in different environments
- Larger samples

  Limited sensitivity and spatial resolution

However:

Sampling more galaxies helps us understand the global properties and the systematics of SNR populations as a function of their environment.
Historically...

- First record of extragalactic SNRs: LMC (radio)
  (Mathewson & Healey 1964)

- Pioneering work of Mathewson & Clarke (1973) on the MCs
  (based on the [SII]/Hα criterion and radio data)

- The SNR census continued primarily by exploiting ground-based
telescopes
  (largest number of extragalactic SNRs in the optical band)

- Advent of multi-λ sensitive observations:
  X-rays: Einstein, ROSAT, XMM, Chandra
  Optical: HST
  Radio: VLA

Last decade: more systematic studies of extragalactic SNR populations
Selection Criteria for detecting SNRs

1. Optical: \([\text{SII}]/\text{H}\alpha \geq 0.4\) (Mathewson & Clarke 1973)

2. Radio: Non-thermal emission

3. X-rays: **soft** (\(\leq 2\) keV) sources with **thermal** emission

4. \([\text{FeII}]\) (1.644 \(\mu\)m) (e.g. Blair et al. 2014)
SNRs in the optical: Emission line diagnostics

Various physical parameters can be estimated:

[SII]/Hα: main shock-heating gas indicator

[NII]/Hα: metallicity indicator, secondary shock-heating gas indicator

[OIII]/Hβ: shock velocity indicator

[SII]6716/6731: electron density indicator

Elemental abundances and shock velocities can be calculated using sophisticated shock models
(e.g. Raymond 1979, Dopita 1984, Allen 2008)
SNRs in irregular galaxies present higher Hα/[NII] ratios (lower metallicities) than those in spirals.
SNRs in the optical: Emission line diagnostics

[NII]/Ha: metallicity and shock-heating gas indicator

- SNRs present higher [NII]/Ha than HII regions
- Higher [SII]/Ha ratios present higher [NII]/Ha ratio values


Blair & Long (1997)
SNRs in the optical: Emission line diagnostics

$\left[\text{NII}\right]/\text{H}$α: metallicity and shock-heating gas indicator

Secondary shock-heating gas indicator

Flatter slope $\rightarrow$ higher $\left[\text{SII}\right]/\text{H}$α
$\rightarrow$ non-uniform ISM ?
SNRs in the optical: Emission line diagnostics

Shock models for measuring abundances and shock velocities

Lee & Lee (2015)

Leonidaki et al. (2013)

Using theoretical shock model grids (of Allen et al. 2008) for different values of shock velocity, magnetic field parameters and chemical abundances.

Alternative method for calculating abundances: X-ray spectra (Maggi et al. 2016)
SNRs in the optical: Age / Evolutionary stage

Cumulative Size Distributions

(Hughes & Helfand 1984 ; Long et al. 1990 ; Gordon et al. 1998 ; Dopita et al. 2010 ; Badenes et al. 2010)

[Graph depicting cumulative size distributions of SNRs in various galaxies, including M31, M33, LMC, SMC, and the Milky Way (MW).]
SNRs in the optical: Age / Evolutionary stage

Surface Brightness - Diameter ($\Sigma$-D relation)
(The $\Sigma$-D relation has also been used to estimate the distances to the MW SNRs; Pavlović et al. 2013)

Blair & Long (1997)

Slight trend for the relatively small diameter objects to have higher surface brightnesses.
Discrimination from superbubbles

- Moderate [S II]/Hα values (0.45 < [S II]/Hα < 0.6)
  (e.g. Lasker 1977; Walterbos & Braun 1994; Chen et al. 2000)

- Large sizes (>100 pc) which are rare among known SNRs
  (e.g. Williams et al. 1999)

- Slower Hα expansion velocities than those of SNRs (<100 km s⁻¹)
  (e.g. Franchetti et al. 2012)

- OB associations

- Their low-density environment is responsible for their rather faint
  X-ray emission (below that of SNRs: 10³⁴–10³⁶ erg/s)
  (e.g. Chu & Mac Low 1990)

- Mainly thermal radio emission
Discriminating progenitors

Criteria for Type II/Type Ia:

1. Distinct type of objects (plerions, oxygen-rich, Balmer-dominated)


4. Type Ia SNRs present relatively low Hα flux compared to Type II SNRs (e.g. Franchetti et al. 2012)

5. Metal abundances:
   - Fe-rich → Type Ia, O-rich → Type II (Hughes et al. 1995, Maggi et al. 2016)
   - Fe Kα line energy centroids: 6.4 keV → Type Ia; 6.7 keV → Type II (Yamaguchi et al. 2014)

The mean diameter of Type Ia remnants is larger than that of the CC remnants. This means that a majority of the CC remnants may lie on dense ambient ISM than the Type Ia remnants.
The Hα and [S II] surface brightnesses of the Type Ia SNR candidates show stronger linear correlations with their sizes than the CC SNR candidates.
Multi-λ properties: Venn diagrams

Long et al. (2010)

Pannuti et al. (2011)

Leonidaki et al. (2013)
Multi-\(\lambda\) properties: Venn diagrams

- Limited sensitivity

- Easier to detect optical SNRs in regions with low density/diffuse emission (Long et al. 2010, Pannuti, Schlegel & Lacey 2007, 2002)

- Missing specific-types of SNRs (Balmer-dominated/oxygen-rich/wind-blown bubbles (optical), plerions(X-rays/radio)

- Evolutionary stage (easier to detect evolved/older SNRs in the optical)

Matonick & Fesen (1997)
**Multi-λ properties: Luminosity relations**

- The most luminous X-ray SNRs tend to be the SNRs with the higher Hα luminosities
- The X-ray luminosities are lower than the Hα luminosities
- No strong correlation
- Large scatter in ratio: Different materials in a wide range of temperatures (Long et al. 2010, Leonidaki et al. 2013)
- Inhomogeneous local ISM around SNRs (Pannuti, Schlegel & Lacey 2007)
Multi-λ properties: Luminosity-shock heated indicator

$L_x - [S\text{II}]/H\alpha$

Because of the long cooling time of the X-ray material, the shock velocity we are measuring does not necessarily correspond to the shock that generated the bulk of the X-ray emission material.

Trend for SNRs with higher $L_x$ to have less $[S \text{II}]/H\alpha$ ratios

Leonidaki et al. (2013)

Lee & Lee (2014)
Multi-λ properties: Luminosity-density

$L_x - [\text{SII}] 6716/6731$

In most cases the higher the density in the [SII] zone the higher the X-ray luminosity.
Multi-λ properties: Luminosity relations

$L_{\text{H}\alpha} - L_{\text{radio}}$, $L_{\text{X}} - L_{\text{radio}}$

No correlation - inhomogeneous local ISM around SNRs
Systematic trend for more luminous SNRs to be associated with irregular galaxies:

- Either due to the typically lower metallicity of irregular galaxies than in typical spiral galaxies (e.g. Pagel & Edmunds 1981; Garnett 2002)
- The non-uniform ISM which is often the case in irregular galaxies
Since core-collapse SNe are the endpoints of the evolution of the most massive stars, their SNRs are good indicators of the current SFR.

Kopsacheili et al. (in preparation)
SNRs and SFR

Since core-collapse SNe are the endpoints of the evolution of the most massive stars, their SNRs are good indicators of the current SFR.
X-ray properties: Environmental effects

Luminosity functions: X-rays

Maggi et al. (2016)
Summing up...

- Revolution on extragalactic SNRs
- Enabled the study of the physical properties of SNRs in different environments (evolutionary stage, progenitors)

But this is just the beginning..

Need to observe more galaxies to larger depths and in a multi-λ context in order to:

- alleviate the selection effects that hamper the current studies of SNRs
- obtain a more complete picture of the SNR populations
SNRs in the optical: Evolution

Cumulative Size Distributions: What happens if X-rays are present?

M33 - Lee & Lee (2014b)

M31 - Lee & Lee (2014a)

\[ \alpha = 2.26 \]

\[ \alpha = 2.21 \]

\[ \alpha = 2.37 \]

\[ \alpha = 2.23 \]
Multi-\(\lambda\) properties: Complete picture

Luminosity functions: Optical

Leonidaki et al. (2013)

Matonick & Fesen (1997)
Multi-λ properties: Luminosity relations

$L_x - L_{\text{H}\alpha}$

ISM around the A-class remnants (complete shells, compact-center bright objects) seems more uniform than that around the B-class (partial shells) remnants

Lee & Lee (2014b)

Lee & Lee (2014a)
SNRs in the optical: Emission line diagnostics

\[ \text{[NII]/H\alpha: abundance gradient} \]

- Dependence on:
  - Clumpy ISM?
  - Progenitors (Type Ia/Type II)?
  - Galaxy type?

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\[ \text{Log}(\text{[NII]} \lambda 6548,83/H\alpha) \]

\[ \text{R}_{GCD} \text{ [kpc]} \]

Lee & Lee (2015)