New Insight into SNR Evolution Revealed by the Discovery of Recombination X-Rays

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Overview and Conclusion

- Until recently, it was believed that all SNRs can be characterized by ionizing (= less-ionized) or nearly-ionization-equilibrium plasma.

- We’ve discovered recombination features in the X-ray spectra of several SNRs, suggesting the presence of recombining (over-ionized) plasma! ... Peculiar SNRs?

- Not peculiar! Recombining state is probably common for a certain type of SNRs!
Ionizing Plasma in Shell-Like SNRs

Shock heating & Collisional ionization

- Shocks are formed due to interaction b/w ejecta and ambient matter
- Ionization proceeds slowly compared to shock heating

Timescale to reach CIE: \( t \sim 3 \times 10^4 \left( n_e / 1 \text{ cm}^{-3} \right)^{-1} \text{ yr} \) (Masai 1984)
  → CIE is not yet achieved in many SNRs in homogeneous ISM

“NEI” (Non-Equilibrium Ionization) ➔ Ionizing (less-ionized)

Low ionized Fe K-shell emissions
- Tycho (e.g., Hwang+1998)
- SN1006 (Yamaguchi+2008)

\( kT_e \sim 2 \text{ keV}, \ n_e t \sim 10^{9-10} \text{ cm}^{-3} \)
  ⇒ Av. charge < 16 (Ne-like)
 cf. 2keV CIE plasma : \( \sim 23.5 \) (Li~He-like)
Recombining Plasma in W49B

\( kT_z \) (ionization balance) > \( kT_e \)
- Emissions from highly ionized atoms
- Free-bound emissions (RRC)

**Recombining (over-ionized)**
- Solar flare
- X-ray binary (photo-ionized)
- SNR ??
  ... Hasn’t been confirmed as yet

**Suzaku observation of W49B**

Discovery of the strong RRC of Fe

\( kT_e \sim 1.5 \) keV, \( kT_z \sim 2.7 \) keV
Clearly over-ionized!!
**W49B (Spatial Distribution)**

Fe He-Kα (6.5-6.8keV)  
RRC (8.5-10keV)

RRC/Kα ratio

2.'5-radius

- keT_e ~ 1.6 keV
- keT_z ~ 2.6 keV

East

- keT_e ~ 1.4 keV
- keT_z ~ 3.0 keV

West

More over-ionized

(Ozawa 2010; D thesis, Kyoto Univ.)

Keohane+2007

RRC/Brems ratio  
(4.4-6.2keV / 8.3-12keV)

XMM: Miceli+2010
Recombination X-Rays from IC443

IC443 (w/ Suzaku)

RRC of Si and S: bared ions → H-like  

\[ kT_e \sim 0.6 \text{ keV} \]
\[ kT_z (\text{Si}) \sim 1.0 \text{ keV} \]
\[ kT_z (\text{S}) \sim 1.2 \text{ keV} \]

Over-ionization is unexpected for standard evolution of SNRs

More detailed spectroscopy to investigate the formation mechanism of recombining plasma!
IC443

Spatially-resolved spectral analysis

Narrow region to avoid mixing of multi plasma components

North rim
- Bright in soft X-rays
- Optical filament
- Pre-existing wind-blown wall (Meaburn+1990)

Region 1
- Brightest in hard (~2-3keV) X-rays
  Red: 0.5-1.0 keV
  Blue: 1.7-3.0 keV
  (Si & S band)
  Contour: optical shell

Region 2
- Lower X-ray luminosity
- Nearer to the PWN

Optical image (DSS)
IC443 (Region 1)

NEI model in SPEX code (Kaastra+)

- Recombining state reproducible
- Assumes Initial ionization balance $kT_z^{\text{init}}$ higher than $kT_e$
- Free parameters:
  - $kT_z^{\text{init}}$, $kT_e$, $n_{e\tau}$ (recomb timescale),
  - Emission measure, Metal abundances

Only one plasma component is needed!!

$N_H = 4.8 \ (4.6-5.0) \times 10^{21} \ \text{cm}^{-2}$

$kT_z^{\text{init}} = 2.0 \ (1.8-2.2) \ \text{keV}$

$kT_e = 0.56 \ (0.55-0.57) \ \text{keV}$

$n_{e\tau} = 4.6 \ (4.2-5.0) \times 10^{11} \ \text{cm}^{-3} \ \text{s}$

$\rightarrow kT_z(\text{Si}) \sim 1.0\text{keV}, \ kT_z(\text{S}) \sim 1.2\text{keV}$

Free-bound dominant in $> 2.0\text{keV}$
IC443 (Region 1)

NEI model in SPEX code (Kaastra+)

- Recombining state reproducible
- Assumes Initial ionization balance $kT_{z^{\text{init}}}$ higher than $kT_{e}$
- Free parameters: $kT_{z^{\text{init}}}$, $kT_{e}$, $n_e t$ (recomb timescale), Emission measure, Metal abundances

Only one plasma component is needed!!

Previous works: RRC not considered
→ Fitted w/ 2-component CIE model to reproduce full band spectra
Amy (Kawasaki+2002): 0.2keV + 1.1keV
XMM (Troja+2008): 0.4keV + 1.3keV

Free-bound dominant in > 2.0keV
IC443 (Reg 2 & North rim)

**Region 2**  
1 component  
kT\text{z}^{\text{init}} = 8.9 (6.4-13) \text{ keV}  
kT_e = 0.25 (0.18-0.31) \text{ keV}  
n_e t = 4.1 (3.9-4.3) \times 10^{11} \text{ cm}^{-3} \text{ s}  
→ kT_z(Si) \sim 0.9 \text{keV}, \ kT_z(S) \sim 1.0 \text{keV}  
- Lower kT_e and kT_z compared to Reg 1  
- RRC dominant in entire energy range  
→ Difficulty in abundance determination

**North rim**  
2 components  
Soft X-rays: 0.2keV CIE plasma  
→ blast-shocked dense bubble wall  
(coincident with bright optical shell)  
Hard X-rays: recombining plasma  
kT_z^{\text{init}} = 2.0 \text{ keV}, \ kT_e \sim 0.6 \text{keV},  
n_e t = 5 \times 10^{11} \text{ cm}^{-3} \text{ s}  
(Similar to Reg 1)
Origin of the Over-Ionization

CIE + Recombining
Soft X-rays from blast-shocked pre-existing wind-blown shell (Coincident w/ Hα)

Recombining
- $kT_e \sim 0.56 \text{ keV}$
- $kT_z(S) \sim 1.2 \text{ keV}$
- $n_e \sim 3 \text{ cm}^{-3}$

Recombining
- $kT_e \sim 0.25 \text{ keV}$
- $kT_z(S) \sim 1.0 \text{ keV}$
- $n_e \sim 1-6 \text{ cm}^{-3}$

uncertainty due to the difficulty in the abundance determination

- Lower luminosity in the south due to the lower temperature ($kT_e$)
- Lower ionization degree ($kT_z$) in the south (near to the PSR)
  → Photo-ionization currently taking place (i.e., off-beam PSR) is not possible
Origin of the Over-Ionization

Params for Region 1

\[
\begin{align*}
k_T^e &\sim 0.56 \text{ keV} \\
k_T^z_{\text{init}} &\sim 2.0 \text{ keV} \\
n^e_t &\sim 5 \times 10^{11} \text{ cm}^{-3} \text{ s} \\
n^e &\sim 3 \text{ cm}^{-3} 
\end{align*}
\]

Initial heating/ionization due to interaction with dense CSM (like SN1993J) & subsequent cooling due to rapid adiabatic expansion?

- \(k_T^e(t)\)
- \(n^e(t)\)

Behavior of shock interacting with CSM (Dwarkadas 2007)

"Forgets" about the existence of the CSM

→ Rapid expansion and cooling can be realized!!
Recomb X-Rays from Other SNRs

**G359.1-0.5**
Ohnishi+ in prep.

**W28**
Sawada+ in prep.

**W44**
Sawada+ in prep.

CIE: \( k_{Te} = k_{Tz} = 0.77 \text{keV} \)

\( k_{Te} = k_{Tz} = 1.0 \text{keV} \)

\( k_{Te} = k_{Tz} = 0.63 \text{keV} \)
Recomb X-Rays from Other SNRs

\[ kT_e = 0.29 \text{keV} \]
\[ kT_z = 0.77 \text{keV} \]

\[ kT_e = 0.37 \text{keV} \]
\[ kT_z = 0.75 \text{keV} \]

\[ kT_e = 0.51 \text{keV} \]
\[ kT_z = 0.71 \text{keV} \]

Mixed-morphology SNRs (Rho & Petre 1998)
Centrally-peaked X-rays w/ radio shell
- Recomb plasma is common for MM-SNRs?
- MM-SNR is a relic of CSM interaction??
Summary

- Discovery of recombination plasma in SNRs
  - Spectrum of IC443 can be reproduced with one-component plasma in recomb state
- Origin would be initial heating due to interaction with dense CSM, like SN1993J
- Recomb plasma may be common for MM-SNRs
  ... New Insight !!
- Understanding of recomb plasma in SNRs will be progressed with ASTRO-H and IXO