Suzaku Observations of Galactic Supernova Remnants to Understand the Formation Process of Recombining Plasmas

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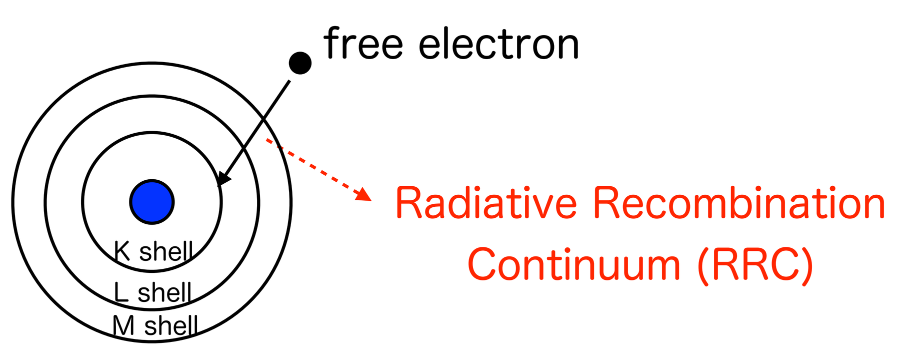
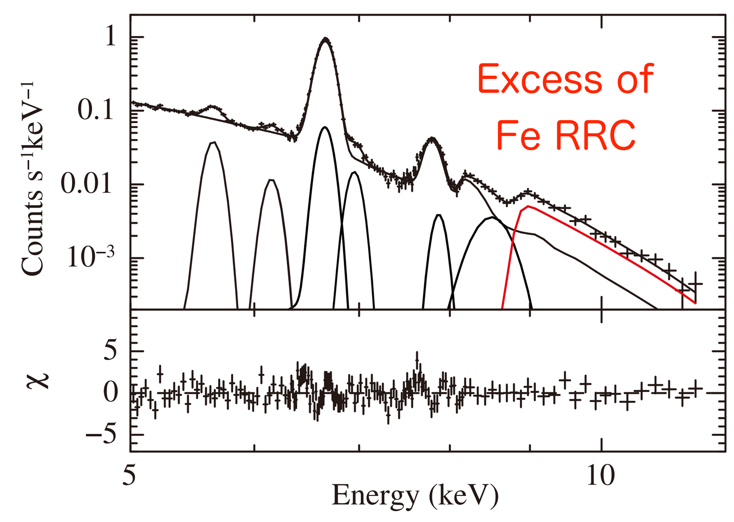
Recombining plasmas (RPs)

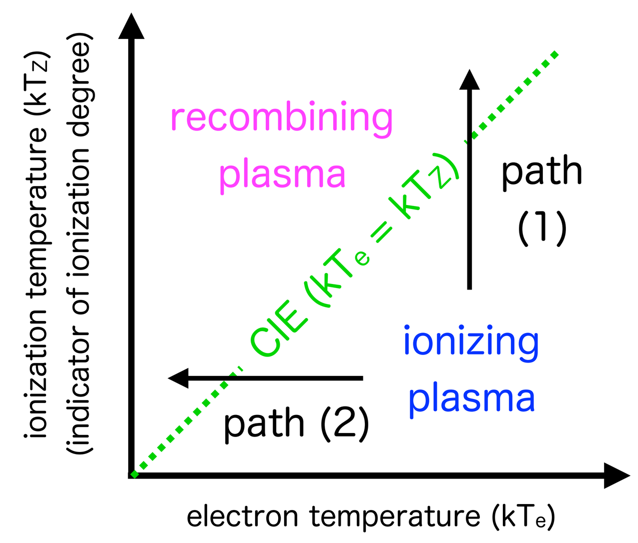
- In a supernova remnant (SNR), a plasma reaches a collisional ionization equilibrium (CIE) after about 10^5 yr. Since most of SNRs have an age of less than a few 10^4 yr, SNR plasmas are naturally expected to have an ionization degree below the equilibrium and to be in an ionization-dominant state (IP; ionizing plasma).
- Recent observations with the Suzaku satellite, however, revealed peculiar plasmas in 16 SNRs, which are in a recombination-dominant state, and thus called recombining plasmas (RPs). Such plasmas are not anticipated in the standard picture of the SNR plasma evolution described above.
- The spectrum of the RRC has an energy edge depending on the binding energy of the recombined electron. The RRC is a clear evidence that the plasma is in a recombination-dominant state.



Suzaku observation of an RP in W49B [1]



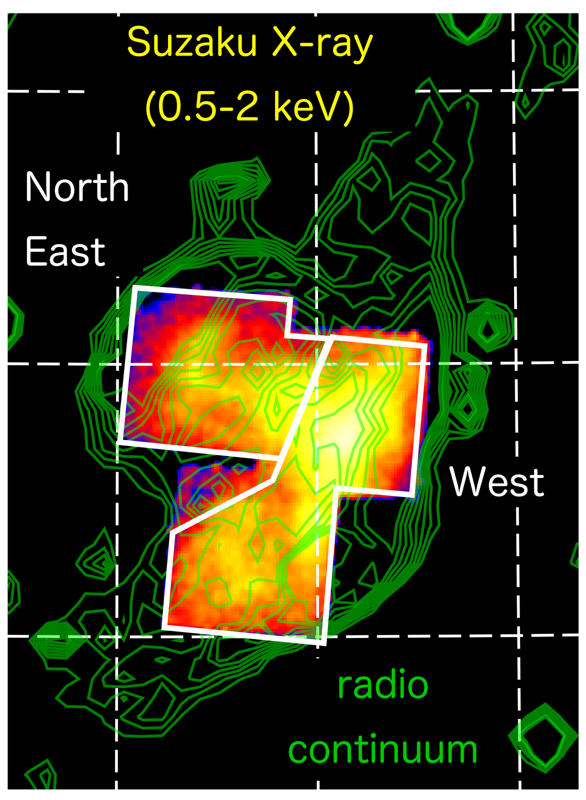
The formation process of RPs

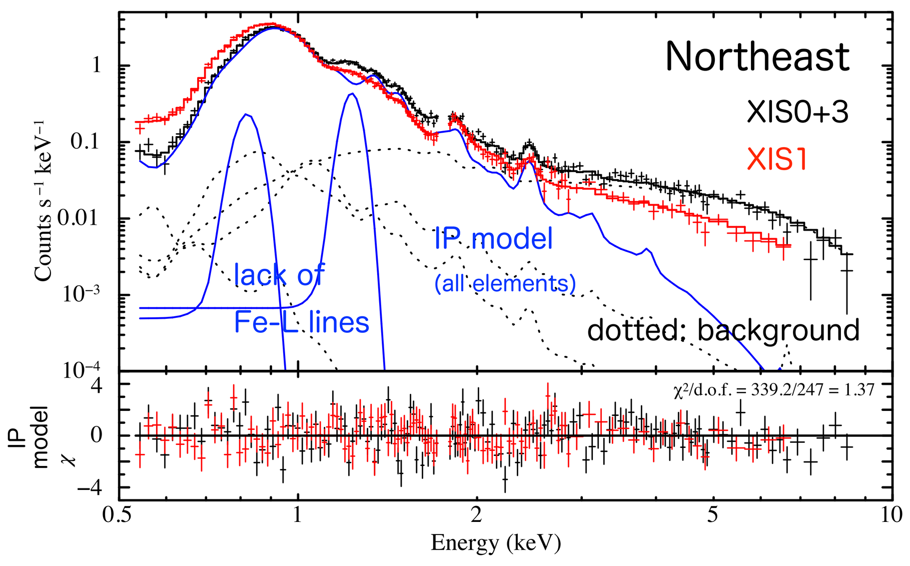


- Paths from ionizing plasmas to recombining plasmas
  - path (1): ionization increase → ✕
    One of scenarios is photoionization, but it is not much debated because candidates of light sources are not found around the SNRs.
  - path (2): kT_e decrease → ○
    Two scenarios; rarefaction and thermal conduction, are mainly considered.
- Rarefaction [2]: If the supernova explodes in a dense circumstellar matter (CSM) around the massive progenitor, the ejecta are shock-heated quickly. Soon after the shock wave breaks the CSM region out to lower density interstellar medium (ISM). Then kT_e cools down by the adiabatic expansion.
- Thermal conduction [3]: If an ionizing plasma encounters to cold molecular cloud, the electron temperature drops rapidly by thermal conduction. Since the recombination timescale of ionized atoms is longer than the conduction time scale, RPs would be realized.

→ A key is distributions of plasma kT_e and ambient gases.

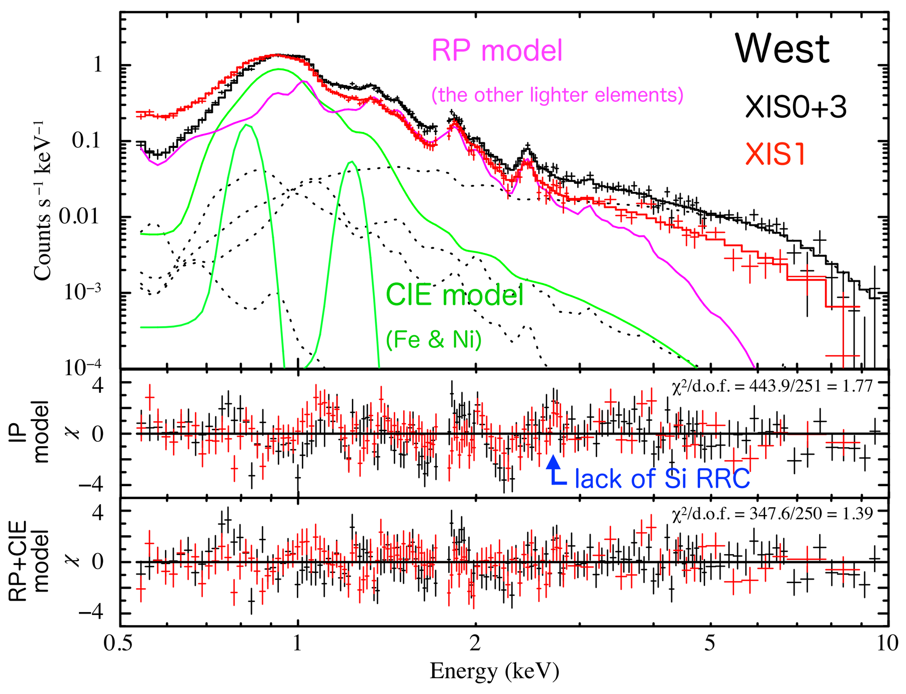
X-ray spectral analyses





The northeast spectrum can be reproduced by the typical IP model.

IP: kT_e = 0.83 ± 0.01 keV, n_et = (4.0 ± 0.7) × 10^{11} cm^{-3} s

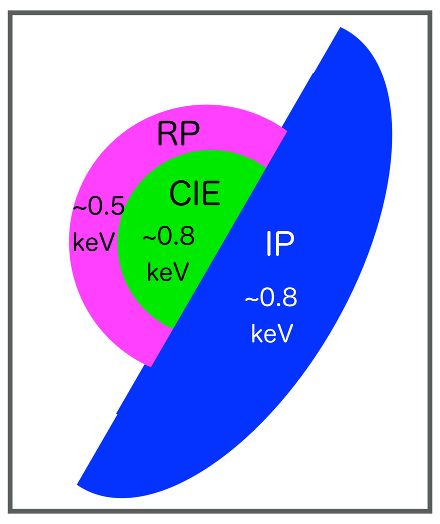


The RP+CIE model is required to reproduce the west spectrum.

CIE: kT_e = 0.87 ± 0.03 keV

RP: kT_e = 0.46 ± 0.03 keV, kT_{init} = 3.0 (fixed), n_et = (6.1 ± 0.5) × 10^{11} cm^{-3} s

To explain the two-components model in the west, different spatial distributions of heavier and lighter elements are considered. The Suzaku image of Si-K is uniform whereas Fe-L image is center-filled [4]. We therefore concluded that the plasma is distributed as shown in the right figure.



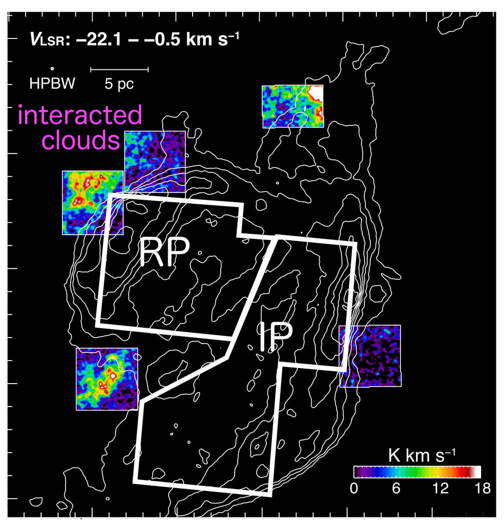
Picture of plasmas in G166.0+4.3

We also analyzed the data of the other SNRs. Detail results of X-ray analyses are available in [4] (G166.0+4.3), [5] (IC 443), and [6] (W44 & W49B).

Comparison between kT_e of the plasmas and ambient gas distributions

• G166.0+4.3 [4]

We found the RP in a port of the SNR. To understand the origin of the RP, we investigated ISM distributions around the SNR. Right figure is a ^{12}CO(J=1-0) image by the Nobeyama 45-m Telescope. We found clumpy CO clouds in four observational regions. The northeastern clouds are shaped along the SNR shell, indicating that the SNR interacts with the clouds.
In the thermal conduction scenario, an RP is anticipated in part of the remnant where blast waves are in contact with cool dense gas. The plasma is cooled from the outside layers. Therefore, it is possible that the plasma is cooled only in the outer part of the northeastern region.

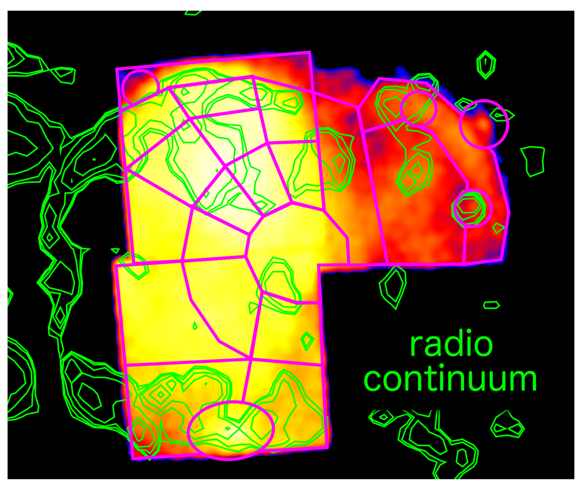


^{12}CO(J=1-0) image by the Nobeyama 45-m with radio continuum

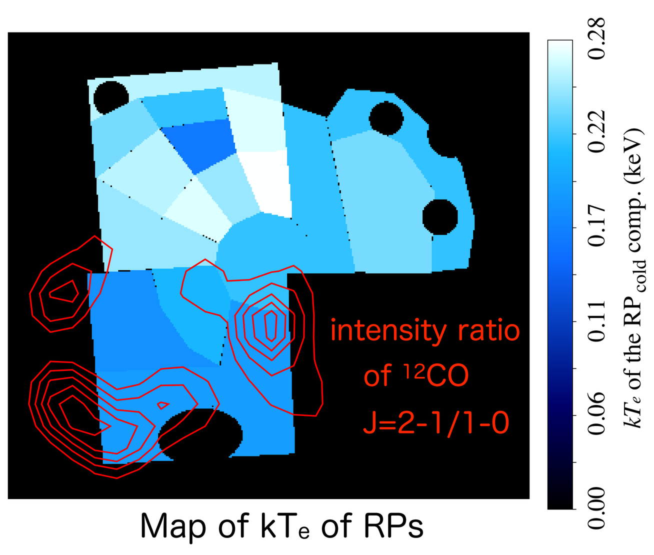
• IC 443 [5]

The emission of IC 443 is well reproduced by a RP model with different kT_e. kT_e decrease toward the southeast where molecular clouds are known to be interacting with the SNR based on the ^{12}CO(J=2-1) to ^{12}CO(J=1-0) intensity ratio [7].

A possible explanation is that the cooling of the plasma in this region is less efficient since the region is far away from the molecular cloud, which would be the major cooling source for IC 443.



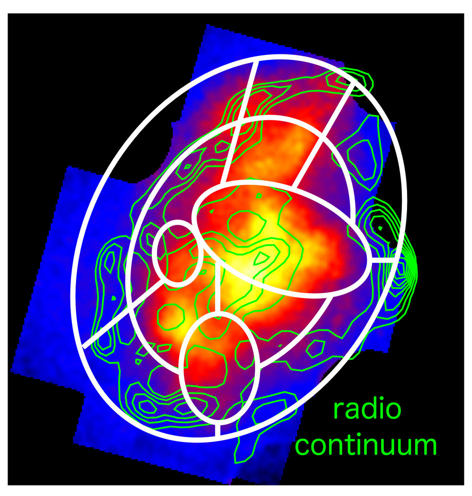
Suzaku X-ray image (0.3-2.0 keV)



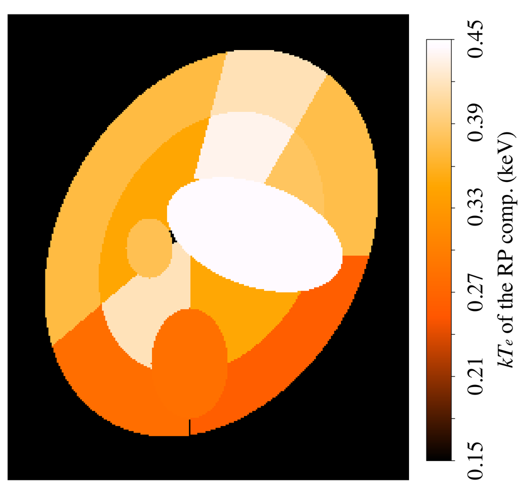
Map of kT_e of RPs

• W44 [6]

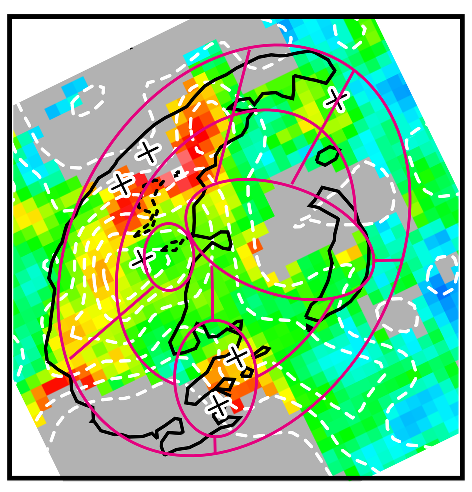
In spectral analyses, we found that kT_e of the RPs in the central part of W44 are higher than those in the outer regions. In the thermal conduction scenario, the SNR plasma is cooled by a molecular cloud as already discussed. The intensity ratio of the ^{12}CO(J=2–1) to ^{12}CO(J=1–0) emissions is distributed in regions excluding these central regions, implying the interaction between the SNR shock and the molecular cloud only in the outer regions.



Suzaku X-ray image (0.3-10 keV)



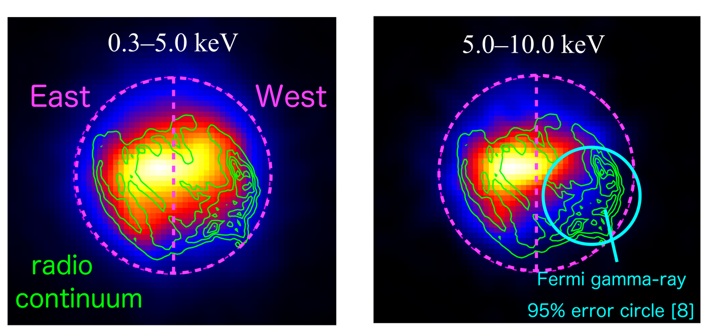
Map of kT_e of RPs



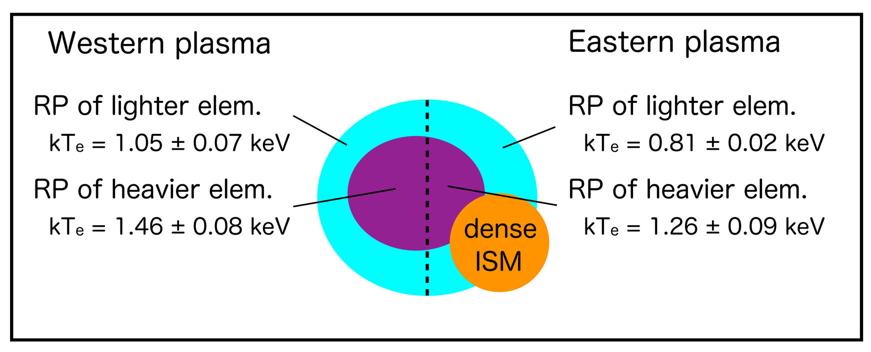
Intensity radio of ^{12}CO J=2-1/1-0 [7]

• W49B [6]

We fitted the wide band spectra and found the ejecta consisting of the two components; the cold RP (lighter element; H-Ti) and the hot RP (heavier element; Cr-Ni). Both the RPs in the west are cooler than those in the east. The Suzaku hard-band image is more compact than the soft band image, suggesting that the hot RP is located at the center. Gamma-ray observations [8,9] found emission on the western side of the SNR, which suggests dense ISM is the west. These result can be simply explained by the thermal conduction between the plasma and ISM.



Suzaku X-ray images in each energy band



Results of kT_e of RPs in W49B

Conclusion

In all the remnants, the spectral analyses revealed good correlations between kT_e and locations of the surrounding molecular clouds.
For the formation process of RPs, the thermal conduction scenario is more suitable than the rarefaction scenario.

Reference

[1] M. Ozawa et al. 2009, ApJ, 706, L71.
[2] H. Itoh & K. Masai 1989, MNRAS, 236, 885.
[3] M. T. Kawasaki et al. 2002, ApJ, 572, 897.
[4] H. Matsumura et al. 2017, PASJ, 69, 30.
[5] H. Matsumura et al. 2017, ApJ, 851, 73.
[6] H. Matsumura, PhD thesis 2018, Kyoto U (URL: http://www-cr.scphys.kyoto-u.ac.jp/d_ron/matsumuraD.pdf)
[7] S. Yoshiike, PhD thesis 2017, Nagoya U
[8] A. A. Abdo et al. 2010, ApJ, 722, 1303
[9] H.E.S.S. Collaboration 2016, arXiv:1609.00600