A deep Suzaku observation of the Galactic Ia supernova remnant G306.3−0.9

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Stratified Structure of Type Ia SNR

SN1006

Tycho

Fe-centered structure is maintained, and Fe are shock-heated later by reverse shock.

Fe-K traces the distribution of the nuclear-burning product. Only 14 samples have been identified as Type Ia SNRs with the Fe-K emission.

Yamaguchi+08

lower ionization Fe-K emission

slower expansion velocity of Fe

Si S Ar Ca Fe

A. Hayato

Observer

Inner

Outside

Blue Shifting

Observer

forward shock

unshocked ejecta

shocked ejecta

shocked ISM

reverse shock

H. Yamaguchi modified

Observer

Inner

Outside

Blue Shifting

Observer
SNR G306.3−0.9

- Discovered with the Swift Galactic plane survey (Miller+11)
- a 5 ks follow-up observation with Chandra (Reynolds +13)
→ 110” radius => age ~ 2500 yr (assuming 8 kpc)

Age is still unknown

Strong low-ionized Fe-K
⇒ Type Ia origin
XMM-Newton (Combi+16), Suzaku (Sezer+17)

CIE plasma for intersteller medium +
Single-NEI plasma for ejecta

- explore the nature of Fe ejecta
- determine the age

Figures 4 and 5 show the XMM-Newton background-subtracted X-ray spectra obtained for the different regions of the SNR. In these figures, the spectra are grouped with a minimum of 16 counts per bin. Error values are 1σ (68.27%) confidence levels for each free parameter and χ² statistics are used.

The spectral analysis was performed using the XSPEC package (Version 12.9.0) (Arnaud 1996) and the emission line information from AtomDB database (Version 3.0.2). The spectra of regions were fit using different models: APEC, NEI, VNEI, PSHOCK, and VPSHOCK, each modified by an absorption interstellar model (PHABS; Balucinska-Church & McCammon 1992). After several tests, we found that the best fit for the individual regions is consistent with a V APEC with sub-solar abundances of Ne and Mg, and a VNEI model (Borkowski et al. 2001), dominated by elevated abundances of Si, S, Ar, Ca and Fe. It is interesting to note that the central region C and the SW region show a strong Fe line at ∼ 6.4 keV, typical of ejecta material, which is also present in the NE region. This two-component plasma model has two electron temperatures, one associated with ejecta material with a hotter temperature kT_{VNEI} and another related to swept-up ISM medium with a lower temperature kT_{VAPC}.
Suzaku Spectrum

![Suzaku Spectrum Graph](image)

Energy (keV):
- Ne
- Mg
- Si
- S
- Ar
- Ca
- Fe

Counts s\(^{-1}\) keV\(^{-1}\):
- XIS0 + 3 (FI)
- XIS1 (BI)
Mesure a gain shift

- The Perseus cluster was observed with XIS one week after the G306.3−0.9.
- Measured with Hitomi SXS (energy resolution of 5 eV).
  → CIE plasma $kT_e = 4.1 \pm 0.1$ keV, $z = 0.01756$
- Compare XIS to SXS
  ⇒ measure a gain shift $\Delta E$.

$\Rightarrow \Delta E = -2 \pm 5$ eV

XIS energy scale at Fe-K is highly reliable at a level of $\leq 7$ eV.
Suzaku Spectrum

\[ \frac{\text{normalized counts}}{\text{s}^{-1} \text{keV}^{-1}} \]

Energy (keV)

- Ne
- Mg
- Si
- S
- Ar
- Ca
- Fe-K\(\alpha\)

XIS0 + 3 (FI)
XIS1 (BI)
Suzaku Spectrum

![Graph showing normalized counts per keV for different elements.

Energy (keV):
- Ne
- Mg
- Si
- S
- Ar
- Ca
- Fe-Kα

Normalized counts s⁻¹ keV⁻¹:
- XIS0 + 3 (FI)
- XIS1 (BI)
Suzaku Spectrum

Fe-Kα 6.47±0.01 keV

XIS0 + 3 (FI)
XIS1 (BI)
Suzaku Spectrum

Fe-Kα 6.47±0.01 keV

Hint of Cr-Kα, Mn-Kα and Fe-Kβ (the significance are 2.1, 1.0 and 1.9σ)

Fe-Kβ

Cr-Kα Mn-Kα
Single-Ejecta Model (same as the previous works)

CIE (ISM) + NEI (ejecta)
Single-Ejecta Model (same as the previous works)

CIE (ISM) + NEI (ejecta)

\[
\chi^2 \text{ (d.o.f.)} = 1.335 \ (773)
\]
Single-Ejecta Model (same as the previous works)

CIE (ISM) + NEI (ejecta)

“N”-shaped residuals (data < model)

χ² (d.o.f.) = 1.335 (773)
Single-Ejecta Model (same as the previous works)

CIE (ISM) + NEI (ejecta)

"N"-shaped residuals (data < model)

→ different ionization timescale between IME and Fe

\[ \chi^2 \text{ (d.o.f.)} = 1.335 \ (773) \]
Two-Ejecta Model

\[ \text{CIE (ISM)} + \text{NEI (IME)} + \text{NEI (Fe)} \]

- \( N_H = 1.3 \times 10^{22} \text{ cm}^{-2} \) (ISM)
- \( kT_e = 0.28 \text{ keV} \) (IME ejecta)
- \( kT_e = 0.98 \text{ keV} \) (IME ejecta)
- \( n_e t = 1.5 \times 10^{11} \text{ cm}^{-3} \text{s} \) (Fe ejecta)
- \( kT_e = 5 \text{ keV} \) (fix)
- \( n_e t = 1.5 \times 10^{10} \text{ cm}^{-3} \text{s} \)

\[ \chi^2 (\text{d.o.f.}) = 1.149 (768) \]
Two-Ejecta Model

CIE (ISM) + NEI (IME) + NEI (Fe)

Fe has one order of magnitude lower $n_e t$ than IME
Two-Ejecta Model

CIE (ISM) + NEI (IME) + NEI (Fe)

Fe-Kα (6.47 keV)  
Fe-Kβ (~ 7.1 keV)

\( N_H = 1.3 \times 10^{22} \text{ cm}^{-2} \) (ISM)  
\( kT_e = 0.28 \text{ keV} \) (IME ejecta)  
\( n_e = 1.5 \times 10^{11} \text{ cm}^{-3} \text{s} \) (Fe ejecta)  
\( kT_e = 5 \text{ keV (fix)} \)  
\( n_e = 1.5 \times 10^{10} \text{ cm}^{-3} \text{s} \)

\( \chi^2 \) (d.o.f.) = 1.149 (768)

Fe has one order of magnitude lower \( n_e \text{t} \) than IME
Two-Ejecta Model

CIE (ISM) + NEI (IME) + NEI (Fe)

Fe-Kα (6.47 keV)
Fe-Kβ (~ 7.1 keV)

“N”-shaped residuals

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Two-Ejecta Model

CIE (ISM) + NEI (IME) + NEI (Fe)

Fe-Kα (6.47 keV)

Fe-Kβ (~ 7.1 keV)

“N”-shaped residuals

Fe-Kβ not reproduced

Fe has one order of magnitude lower net than IME

$\chi^2 (d.o.f.) = 1.149 (768)$
Two-Ejecta Model

CIE (ISM) + NEI (IME) + NEI (Fe)

Fe-Kα (6.47 keV)
Fe-Kβ (~ 7.1 keV)

"N"-shaped residuals

Fe-Kβ not reproduced

Fe has one order of magnitude lower \( n_{\text{Fe}} \) than IME

\[ \chi^2 (\text{d.o.f.}) = 1.149 \ (768) \]
"N"-shaped residuals

The observed Fe-line parameters, Fe-Kα (6.47 keV), Fe-Kβ (~ 7.1 keV), and (c) the Kα centroid are linked with the corresponding ionization ages (non-X-ray background). No significant change is found in the range. The Gaussian widths (FWHM) of the Mn Kα and 3 lines in panel (c) indicate the 1 with the corresponding ionization ages (Palmeri et al. 2003, 2004, 2008). For Fe Kα and Fe Kβ, we calculate rate coefficients for collisional excitation and emission. We calculate rate coefficients for collisional excitation and emission. We calculate rate coefficients for collisional excitation and emission.

The inconsistency among the three diagnostics indicates the presence of lower-net Fe.
The Three-Ejecta Model involves the following components:

1. **CIE (ISM)**: The ionic contribution of the ISM.
2. **NEI (IME)**: Neutral emission from the IME ejecta.
3. **NEI (high-n<sub>e</sub> Fe)**: Neutral emission from high-density Fe ejecta.
4. **NEI (low-n<sub>e</sub> Fe)**: Neutral emission from low-density Fe ejecta.

### Parameters

- **N<sub>H</sub>** = 1.3 \( \times 10^{22} \) cm<sup>-2</sup>
- **kT<sub>e</sub>** = 0.27 keV (ISM)
- **n<sub>e</sub>** = 1.8 \( \times 10^{11} \) cm<sup>-3</sup> s (Fe ejecta)
- **kT<sub>e</sub>** = 5 keV (fix) (low-n<sub>e</sub> Fe)
- **n<sub>e</sub>** = 2.1 \( \times 10^{10} \) cm<sup>-3</sup> s (low-nt Fe)
- **kT<sub>e</sub>** = 5 keV (fix)
- **n<sub>e</sub>** = 7.5 \( \times 10^9 \) cm<sup>-3</sup> s

The goodness of fit is given by

\[ \chi^2 \text{ (d.o.f.)} = 1.126 (766) \]
Three-Ejecta Model

CIE (ISM) + NEI (IME) + NEI (high-n_e Fe) + NEI (low-n_e Fe)

$\chi^2$ (d.o.f.) = 1.126 (766)

Fe-Kα (6.47 keV)

Fe-Kβ (~ 7.1 keV)

$N_H = 1.3 \times 10^{22}$ cm$^{-2}$ (ISM)

$kT_e = 0.27$ keV (IME ejecta)

$n_e = 1.8 \times 10^{11}$ cm$^{-3}$s (Fe ejecta)

$kT_e = 5$ keV (fix)

$n_e = 7.5 \times 10^9$ cm$^{-3}$s (low-n_e Fe)

$kT_e = 5$ keV (fix)

$n_e = 2.1 \times 10^{10}$ cm$^{-3}$s (Fe ejecta)

$kT_e = 0.93$ keV (IME ejecta)

$kT_e = 0.27$ keV (ISM)
Discussion

Nature of Fe ejecta

Fe-dominated ejecta has
- one-order-of-magnitude lower $n_eT$
- higher temperature

→ Fe has recently shock-heated by reverse shock. The ejecta stratification is still maintained.

additional “lower-ionized Fe ejecta” component

the possibilities of
- anisotropy of reverse-shock
- non uniformity of ejecta
Discussion

Distance and Age

- Distance
  (fit result) \(N_H = 1.2 - 1.3 \times 10^{22} \text{ cm}^{-2}\)
  (Galactic total) \(\Sigma N_{H_{\text{I}+H_2}} \approx 1.18 \times 10^{22} \text{ cm}^{-2}\)
  → likely on the edge of the Galaxy (d ~ 20 kpc)
- Forward shock-velocity (from kTe of ISM)
  → \(v \sim 490 \text{ km s}^{-1}\)

- \(t_{\text{sedov}} = 0.4R/v \sim 8500 \text{ yr}\)
- one of the most thermally evolved Type Ia SNRs.
- mixing of ejecta is not so effective in a relatively later stage of the Sedov phase
We analyzed the Suzaku data of the SNR G306.3−0.9.

Spectrum analysis showed the Fe-Kα centroid is 6.47±0.01 keV.

Fe-dominated ejecta has

- one-order-of-magnitude lower \( n_e t = 2.1 \times 10^{10} \text{ cm}^{-3} \text{ s} \)
- higher \( kT_e > 3 \text{ keV} \)

than IME-dominated ejecta, indicating Fe has recently shock-heated by reverse shock.

To explain Fe-Kβ, additional “lower-ionized Fe ejecta” component is needed.

The Hydrogen absorption column density \( 1.2-1.3 \times 10^{22} \text{ cm}^{-2} \)
leads to the conclusion that the SNR age is ~ 8.5 kyr.

Mixing of ejecta is not so effective in a relatively later stage of the Sedov phase.