Probe Charge Exchange, Resonant Scattering, and Galactic Hot ISM Absorption in Magellanic Cloud SNRs with High-resolution X-ray Spectroscopic Study of Oxygen Lines

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I. Introduction

High-resolution X-ray spectroscopy of supernova remnants (SNRs) provides profound insights into the radiation mechanisms and chemical compositions of ejecta, circumstellar material (CSM), and interstellar medium (ISM), significantly advancing our understanding of shock physics, progenitor type, explosion mechanism, and remnant evolution (e.g., Katsuda2023). Particularly, line ratios of He/H-like ions, e.g., O VII G-ratio and O VIII Lyβ/α, play an important role in diagnostics on temperature and ionization age (e.g., Porquet+2010). However, due to the complex nature of SNRs, they can be affected by different mechanisms such like charge exchange (CX), resonant scattering (RS), and hot gas absorption.

We carried out high-resolution X-ray spectroscopic study of O lines in several Magellanic Cloud SNRs based on XMM-Newton RGS observations, in order to constrain the contributions of these mechanisms to their X-ray emission.

I. SN 1987A

SN 1987A is the nearest SN observed since Kepler's SN of 1604. Although its X-ray spectra can be approximately fitted by thermal emission models (e.g., Sun+2021), residuals remain at the O lines.
We found O VII G-ratio ≥1 and O VIII Lyβ/α ratio ≥0.2 in SN 1987A (Figure 1), which cannot be fully explained by NEI effects (Figure 2).
We explored the contribution of CX with the acx2 model in PyXspec and the role of RS effect with Monte Carlo simulations. However, ***CX and RS are both disfavored to be the origin, based on spectral fittings and Monte Carlo simulations***.

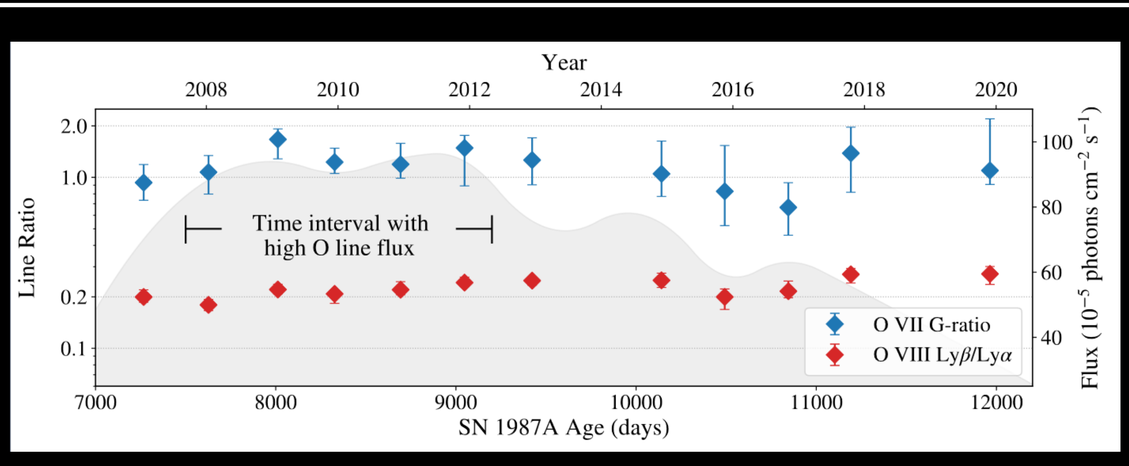

Figure 1. O line ratios and their temporal evolutions in SN 1987A. The blue and red data points denote the O VII G-ratio and the O VIII Lyβ/α flux ratio, respectively. The gray under-filled curve indicates the temporal evolution of the total O line flux (O VII Heα + O VIII Lyα).

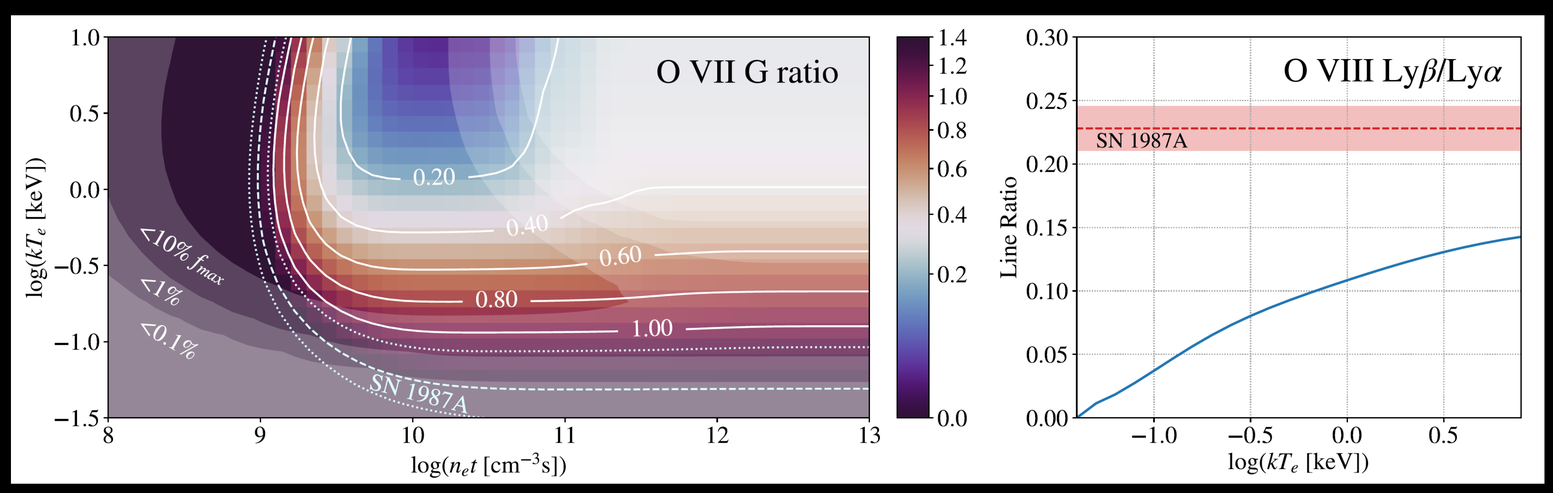

Figure 2. Left: O VII G-ratio as a function of kT_e and $n_e t$ for NEI plasma. The observed G-ratio for SN 1987A is indicated by cyan dashed contours. Shaded contour regions indicate the levels of total O VII Heα flux, as <10%, <1%, and <0.1% of the maximum. Right: O VIII Lyβ/α ratio as a function of kT_e, for both NEI and CIE plasma. The observed flux ratio is indicated by the red region.

We suggest the absorption of fore-ground hot gas as the most likely origin, which plays the major role in modifying resonance line fluxes.
Based on this scenario, we obtained a temperature as $kT_e \sim 0.18$ keV and an oxygen column density as $N_{\rm O} \sim 0.8 \times 10^{16}$ cm^{-2}, which is consistent with ***the hot ISM in the Galactic halo***.
We revised the O abundance of SN 1987A, which is underestimated by ~20% in previous X-ray results.

III. Other SNRs

For those SNRs with moderate angular size (< 3'), RGS is able for spatially-resolved spectroscopic study of O VII triplet lines, which is crucial for determining the radiation mechanism.
Here, we present the exposure-corrected RGS dispersion images of O VII resonance and forbidden lines for four Magellanic SNRs, and map the spatial distributions of forbidden-to-resonance (f/r) flux ratios (Figure 3).
The f/r show significant spatial variation in all 4 SNRs. A high f/r associated with high H density may be indicative of CX origin, while a high f/r associated with high O VII emission measure (thus a high optical depth) may be indicative of RS origin. Meanwhile, hot ISM absorption may work on all 4 SNRs.

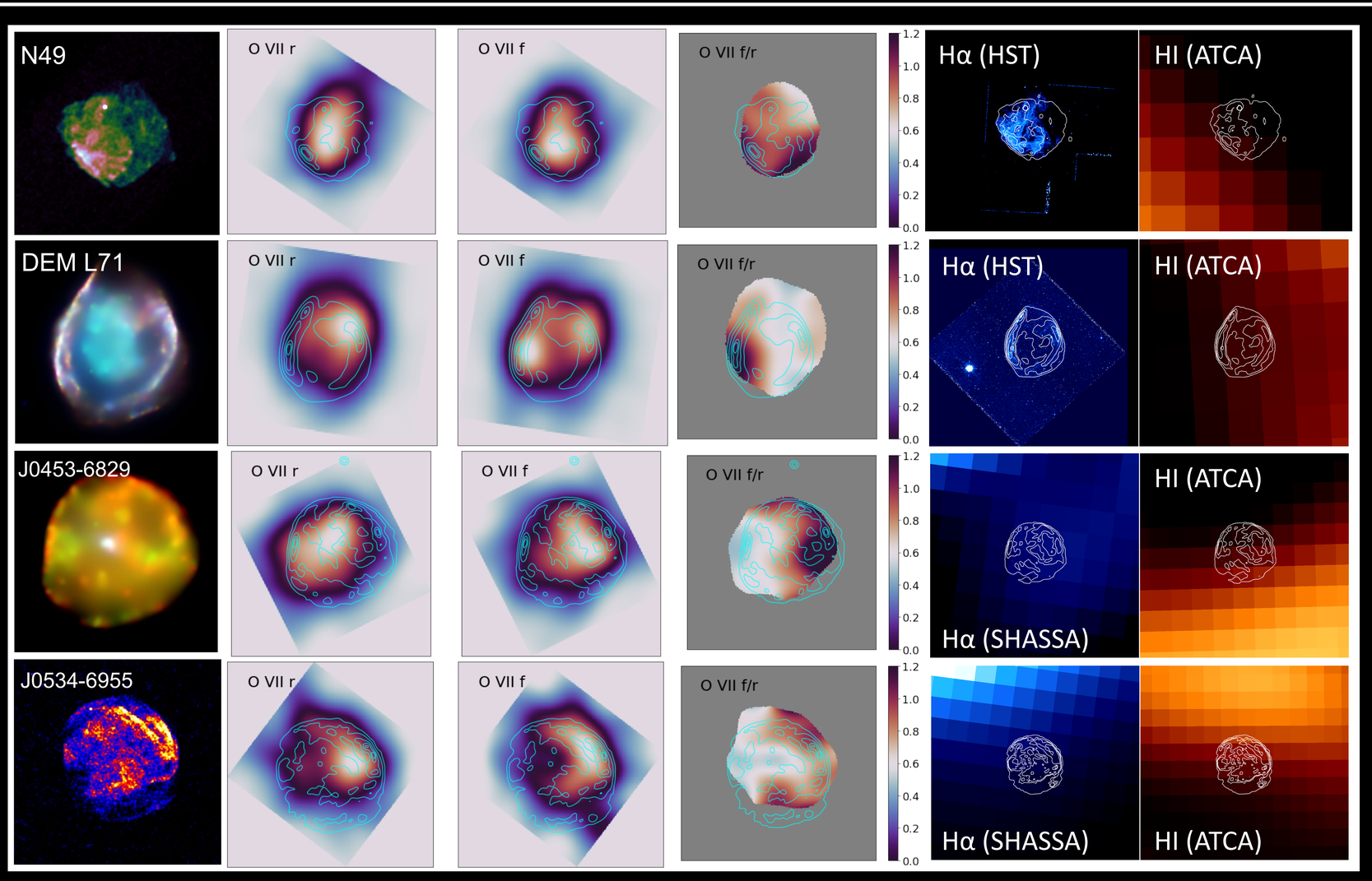

Figure 3. Spatially-resolved spectroscopic study of O VII lines of four Magellanic SNRs. Column 1: X-ray image of the remnant. Column 2&3: normalized surface brightness of O VII resonance line and forbidden line. Column 4: spatial distribution of the O VII forbidden-to-resonance line ratio.. Column 5&6: Hα and HI emission in and around the remnant, compared with X-ray contours.

References: Katsuda, S., 2023, arXiv: 2302.13775
Porquet, D., Dubau, J., & Grosso, N. 2010, SSRv, 157, 103
Sun, L. et al. 2021, ApJ, 916, 41

Bio: Lei Sun is now a postdoctoral researcher at Nanjing University. He obtained his PhD degree in 2022 from a conjoint program between NJU and UvA-API. His major academic interest lies in high-energy astrophysics, X-ray astronomy, and SNR/ISM physics.
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