Evolution of the X-ray Remnant of SN 1987A

Aravind P. Ravi[1], Sangwook Park[1], Svetozar Zhekov[2], Kari Frank[3], David Burrows[4], Marco Miceli[5], Salvatore Orlando[6]

1 UNIVERSITY OF TEXAS ARLINGTON
2 BULGARIAN ACADEMY OF SCIENCE 1869
3 Northwestern CIERA CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS
4 PennState Eberly College of Science
5 UNIVERSITÀ DEGLI STUDI DI PALERMO
6 INAF ISTITUTO NAZIONALE DI ASTROFISICA

Abstract

Based on continuing observations in the X-ray energy band using Chandra X-ray Telescope, we present the latest evolution of the X-ray remnant of SN 1987A. We present a high-resolution spectroscopic analysis using our latest deep (340 ks) Chandra HETG observation in March 2018. We find significant changes in the atomic X-ray line flux ratios (among Si and Mg ions) over the last decade or so, suggesting changes in the thermal conditions of the X-ray emitting plasma. Changing electron temperatures and volume emission measures suggest that shocks moving through the inner ring have started interacting with less dense CSM, probably beyond the inner ring. We do not observe any clear evidence of abundance enhancement yet, suggesting that X-ray emission from the reverse-shocked ejecta is not yet significant.

Background

- SN 1987A, a core collapse supernova, was the nearest (d ~ 51 kpc in the LMC) and hence apparently brightest supernova since Kepler's supernova (1604 AD).
- Owing to its proximity, SN 1987A can be detected and resolved even ~30 years after explosion. Thus, it is a unique astrophysical laboratory for the detailed study of the birth of a supernova remnant and a neutron star.
- The excellent spatial and spectral resolution of the Chandra X-ray Observatory (CXO) has been used to study the photometric, morphological, and spectroscopic evolution of SN 1987A. **We have been observing SN 1987A roughly every 6 months for the past 20 years (total 45 observations as of September 2019) as part of our Chandra monitoring program** [eg., 1, 2, 3, 6, 8, 10]
- We use the High Energy Transmission Grating (HETG) aboard CXO to obtain high resolution dispersed X-ray spectrum of SN 1987A from which we can detect detailed atomic emission lines (Fig 1). In particular, we performed our 5th **deep (340 ks) spectroscopic observation with CXO HETGS in March 2018** to perform a detailed spectral study of the recent X-ray emission from 1987A, probably in a new evolutionary stage (as suggested by [10]).
- X-ray flux from 87A has been dominated by the shock interaction with the dense "inner ring", and it increased as the shock approached and heated the dense clumpy circumstellar medium of the inner ring at ~5000 days since the explosion (~2002) [2]. As the shock entered the main body of the inner ring at around 2004 (~6200 days since SN), the soft X-ray light curve (LC) showed a sharp upturn [3]
- There was a deceleration in the expansion rate of the X-ray remnant [6] at around 2004 (~6200 days since SN), consistent with the interpretations for the shock entering the main body of the inner ring as suggested by the soft X-ray LC. After 2004, till 2016 (~10,500 days) this rate has stayed a constant at ~1600 km/s [9].
- Thermal parameters and elemental abundances were derived from spectral model fits of deep grating observations [e.g., 4,5,7]. The X-ray spectrum of 87A was fitted with two characteristic components - kT ~ 0.56 and 2.43 keV (e.g., March 2007 : day ~7300), representing emission from shock interaction with high and low density CSM, respectively [7]. We call these the soft and hard components, respectively.
- Based on the deep HETG 2007 and 2011 data sets, SN 1987A's X-ray spectra were modelled as the weighted sum of the non-equilibrium-ionization (NEI) emission from two simple 1-D hydrodynamic simulations to reproduce all observed radii and light curves [9].
- In this work, we present the preliminary results from our continuing X-ray study of 1987A, primarily based on our latest deep Chandra data obtained in March 2018.

References

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Results

- Following the spectral modellings of the broadband X-ray spectrum of SN 1987A in literature [e.g., 5,7], we perform a similar two NEI shock component model fits for our new CXO data (March 2018) of 87A (Fig 1).
- All spectra from deep observations (day ~ 6300 to day ~11,300) were re-extracted and re-analyzed using the latest calibration (Chandra CalDB v4.8.5).
- **The He-like to H-like line flux ratio for Si and Mg considerably decline (by ~40%) between day ~9000 (2011) and day ~11,300 (2018) (Fig 2).** Follow-up observations from CXO can shed more light on this trend.

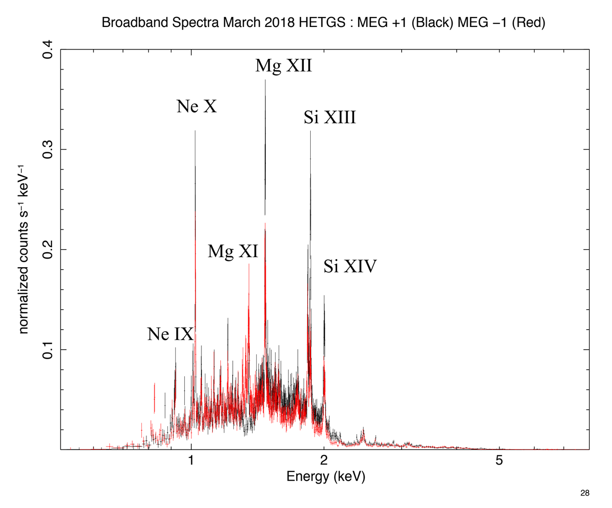

Fig 1: The 1st order dispersed X-ray spectrum [MEG +1 (black) MEG-1 (red)] of SN 1987A based on our 340 ks Chandra HETGS observation taken in March 2018.

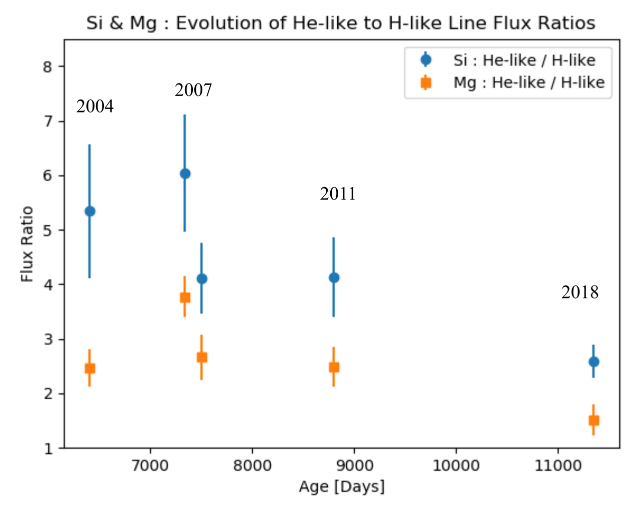

Fig 2: Temporal evolution (~ 6500 to ~ 11,300 days) of He-like / H-like ion line flux ratios of Si and Mg

- Between 2011 and 2018, forbidden (F) and resonance (R) lines from the He-like triplets (e.g., Si XIII & Mg XI) and the Lyα line from the H-like doublets (eg: Si XIV & Mg XII) underwent significant changes for both Si and Mg. **Relative to (F) and (R) lines, the Lyα strengthened for Si and Mg (day ~11,300 (2018)), which results in the decreasing He-like / H-like line flux ratios (Fig 3 & 4).**
- Between 2004 and 2007, electron temperatures for the soft component had remained nearly stationary, while that for the hard component gradually decreased (see Fig 5). We find that **between 2011 and 2018, electron temperatures for the soft component (kT ~0.7 keV) and hard component (kT ~2.4 keV) have increased by ~18% and ~25%, respectively** (Fig 5).
- **The electron temperature ratio between hard and soft component emission stopped decreasing since 2011 (day ~9000)** (Fig 6).
- While **between 2004 - 2011, the volume emission measure (EM) ratio between the soft and hard components had stayed constant around 2, it has decreased by ~41% in our latest March 2018 observation**. (Fig 7). This is due to the decrease of the soft component EM in 2018 (while the hard component continues to increase) (Fig 8).
- **No significant abundance evolution observed between days ~7,500 (2009) and ~11,300 (2018).**

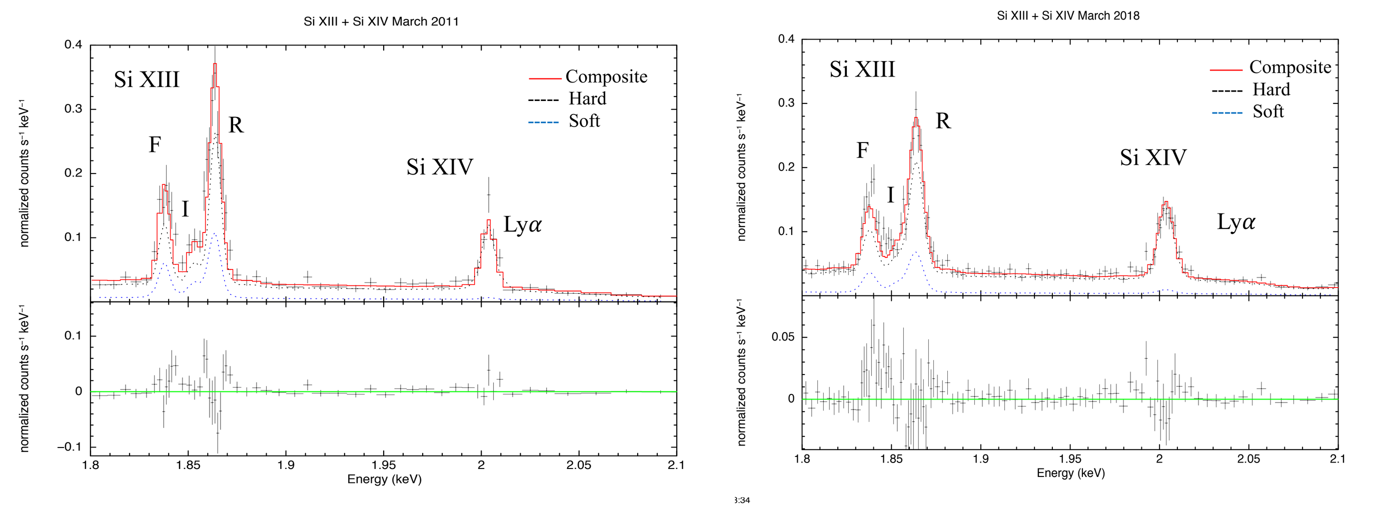

Fig 3 : 3a (Left) Si XIII and XIV lines detected in March 2011 (~ day 9000) ; 3b (Right) Si XIII and XIV lines detected in March 2018 (~day 11,300). Soft component(blue), hard component(black) and the composite two component model(red) show the models used for fitting data in 3a & 3b.

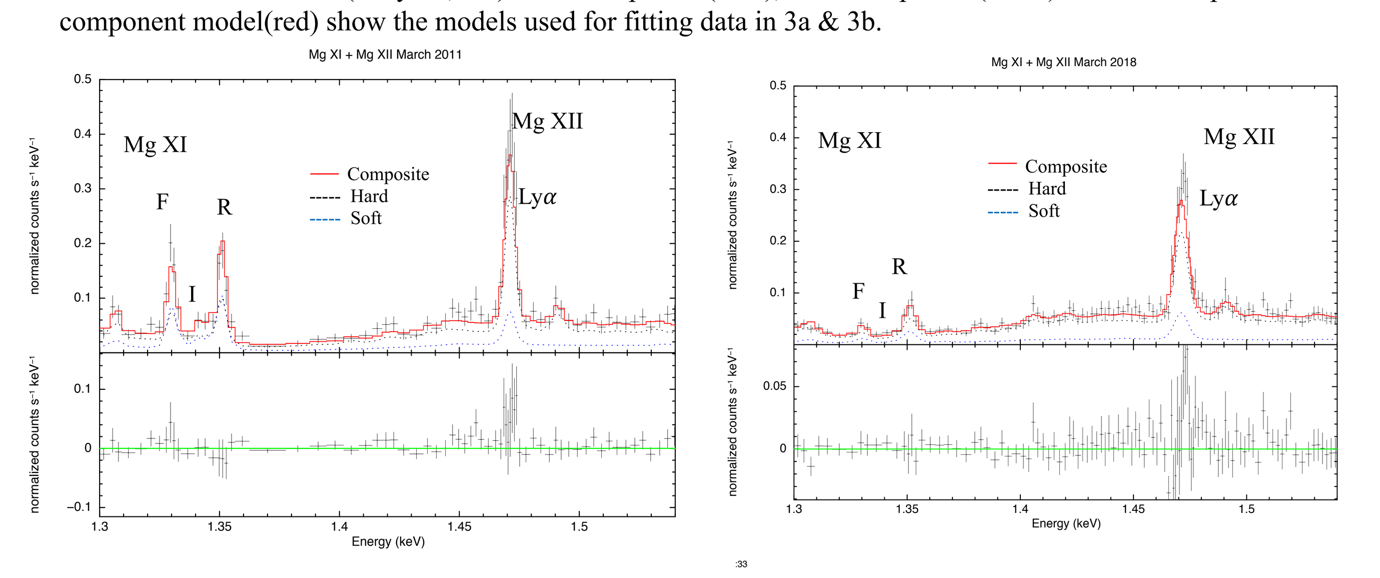

Fig 4 : 4a (Left) Mg XI and XII lines detected in March 2011 (~ day 9000) ; 4b (Right) Mg XI and XII lines detected in March 2018 (~day 11,300). Soft component(blue), hard component(black) and the composite two component model(red) show the models used for fitting data in 4a & 4b.

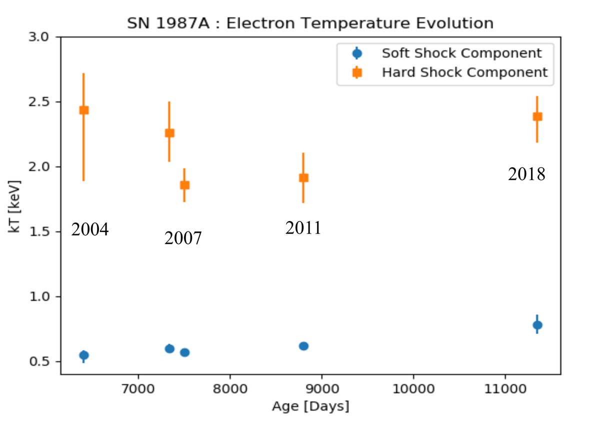

Fig 5 : Evolution of electron temperature for soft and hard shock components over five epochs from ~ 6500 to ~ 11,300 days.

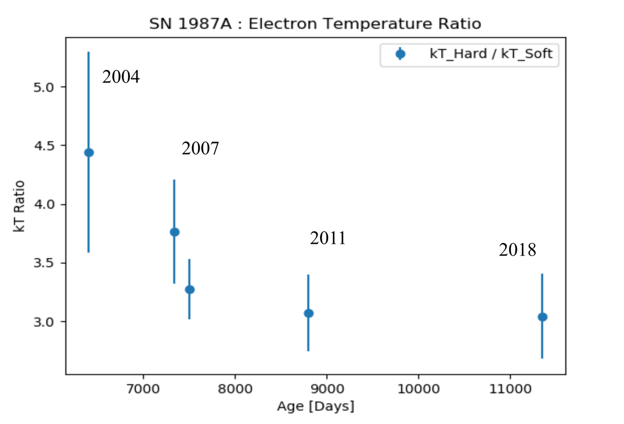

Fig 6 : Temporal evolution (~ 6500 to ~ 11,300 days) of electron temperature ratio of hard component to soft component. Plot shows that the rate of "softening" has reduced over five epochs.

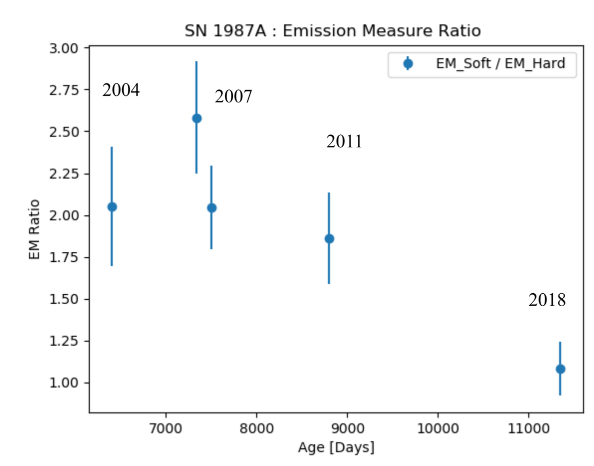

Fig 7 : Temporal evolution (~6500 to ~11,300 days) of volume emission measure ratio between soft and hard shock components.

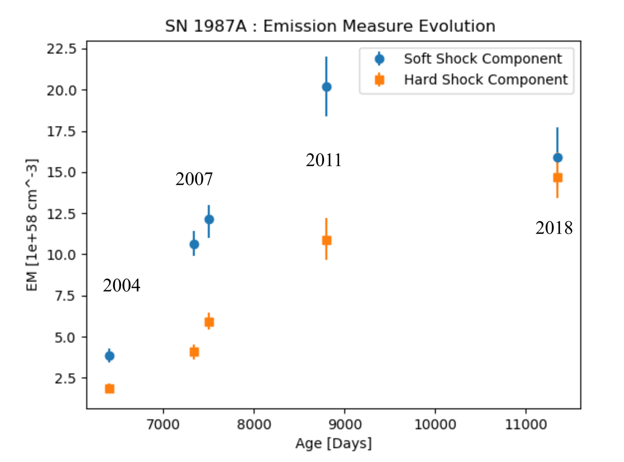

Fig 8 : Evolution of volume emission measure for soft and hard shock components over five epochs from ~6500 to ~11,300 days derived from best-fit normalization.

Conclusions

- The latest evolution in the electron temperatures and volume emission measures for the soft and hard emission components suggest that the shocks moving through the inner ring (which are responsible for most of the X-ray emission) have started interacting with less dense CSM since 2011 (day ~9000). Continuing observations would be crucial in setting the right physical picture.
- There is a significant decrease in the He-like / H-like line flux ratios for Si and Mg as observed in 2018 (day ~11,300). Changing evolution trends of electron temperature for soft and hard component emissions, before and after 2011 (day ~9000) have caused significant changes in the spectral shape around strong Si and Mg lines. These could be the primary drivers for the changing line flux ratios, probably because of the changing density of electrons being shocked. The reverse shock moving through less dense material towards the center may also have contributed in the observed line flux ratio change, but we do not find any clear evidence of a significant abundance increase between days ~7500 (2007) and ~11,300 (2018).
- We will quantitatively assess the origins for changing plasma conditions from March 2018, by comparing them with the synthetic spectra produced using hydrodynamic simulations [eg : 12,13] to quantify various assumptions on the shock evolution through the interactions with the inner ring, ejecta, and beyond.