Evolution of the X-ray Remnant of SN 1987A

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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, updated X-ray light curves as of 2019 March and the radial expansion rate of the remnant as of September 2018. Using our latest deep (340 ks) high resolution dispersed spectroscopic observation, we find significant changes in the atomic X-ray line flux ratios (among Si and Mg ions) over the last decade or so. Our initial results here indicate temporal changes in plasma conditions of the X-ray emitting hot gas, heralding the emergence of a new phase in the evolution of SN 1987A.

Motivation & Strategy

- SN 1987A, a core collapse supernova, was the nearest (d ~ 50 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.
- We use the excellent spatial and spectral resolution of the Chandra X-ray Observatory (CXO) 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 44 observations as of March 2019) as part of our Chandra monitoring program** [eg., 1, 2, 3, 6, 8, 9]
- 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 3). 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 [9]).

Background

- Evolution of the remnant between 1999 (~4600 days) and 2016 (~10,500 days) was studied photometrically [eg., 2,3,8,9], morphologically [eg., 6,9] and spectroscopically [eg., 4,5,7].
- 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 enters the main body of the inner ring at around 2004 (~6200 days since SN), the soft X-ray LC showed a sharp upturn [3] (Fig 1).
- There was a sharp downturn 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]. (Fig 2).
- Plasma parameters and elemental abundances were derived from spectral model fits of deep grating observations [eg., 4,5,7]. The X-ray spectrum of 87A was fitted with two characteristic components with kT ~ 0.56 and 2.43 keV (eg March 2007 : day ~7300), representing emission from shock interaction with high and low density CSM, respectively. [7]
- In summary, SN 1987A has undergone multiple phases of evolution marked by distinct associated physical phenomena. In this work, we present the preliminary results from our continuing X-ray study of 1987A primarily based on our latest Chandra data (taken in 2016 - 2019).

References

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[5] Zhekov et al. 2006, ApJ, 645,293.
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[9] Frank et al. 2016, APJ, 829,40.
[10] Fransson et al. 2015 ApJL, 806, L 19
[11] Cendes et al. 2018, ApJ 867,65
[12] Miceli et al. Conference Talk (Session 4)
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Results

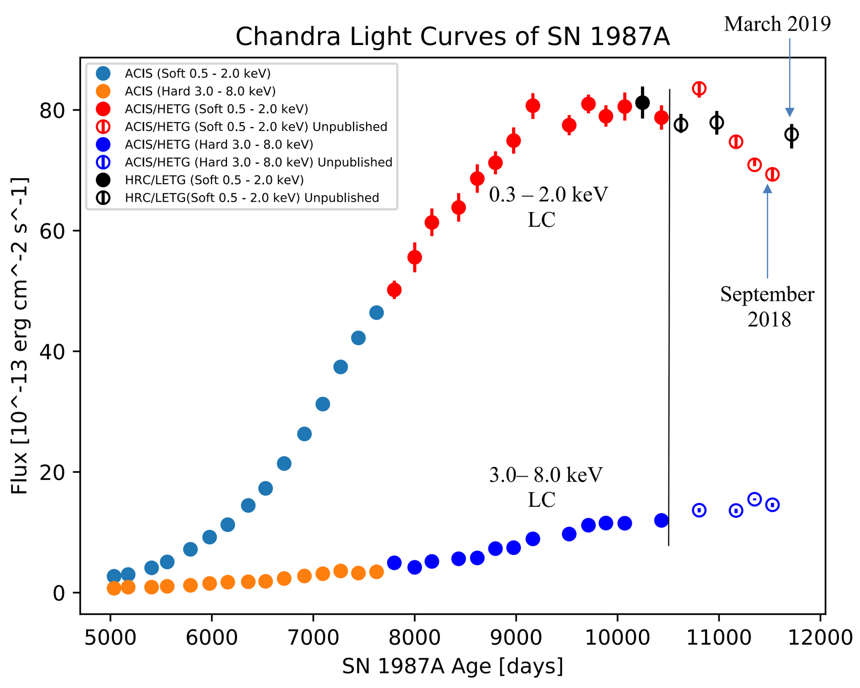

Fig 1: Soft (0.5-2.0 keV) and hard (3.0-8.0 keV) LCs. Data before the vertical line have been published. (eg., [9]).

X-ray Light Curves

- In 2016 (at day ~10,800), the soft band (0.5-2.0 keV) X-ray LC started decaying. As of September 2018 (~11,500 days), the soft band flux was ~6.9 x 10^{-12} erg cm^{-2} s^{-1}, ~ 15% lower than the previously-reported constant rate of ~ 8 x 10^{-12} erg cm^{-2} s^{-1} [9] (Fig 1).
- We note that the soft X-ray flux increased by ~ 10 % in March 2019 (~11,700 days) (Fig 1). The origin of this change is unclear. Follow-up CXO monitoring will be essential to test the nature of this latest LC.
- The hard band (3.0-8.0 keV) X-ray LC continues to increase linearly. (Fig 1)

X-ray Radial Expansion Rate

- The overall soft band expansion rate seems to stay at ~1600 km/s since day ~6000 (Fig 2), which is consistent with our previous results [9].
- In the last ~3 years, there is a hint of "increasing" rate (since day ~ 11,000) after nearly a "constant" rate (days ~9800 -11000)(Fig 2). While this interpretation may be premature with the current X-ray data, it is interesting to note that similar increase of expansion rate was recently reported in the radio band. [11]
- Recent optical images show evidence for the shock propagating into low-density medium beyond the inner ring [10], which may also support the faster expansion rate in our latest X-ray data.
- Our continuing CXO observations for the expansion rate of SNR 1987A would be critical to test this intriguing feature in the expansion of SN 1987A.

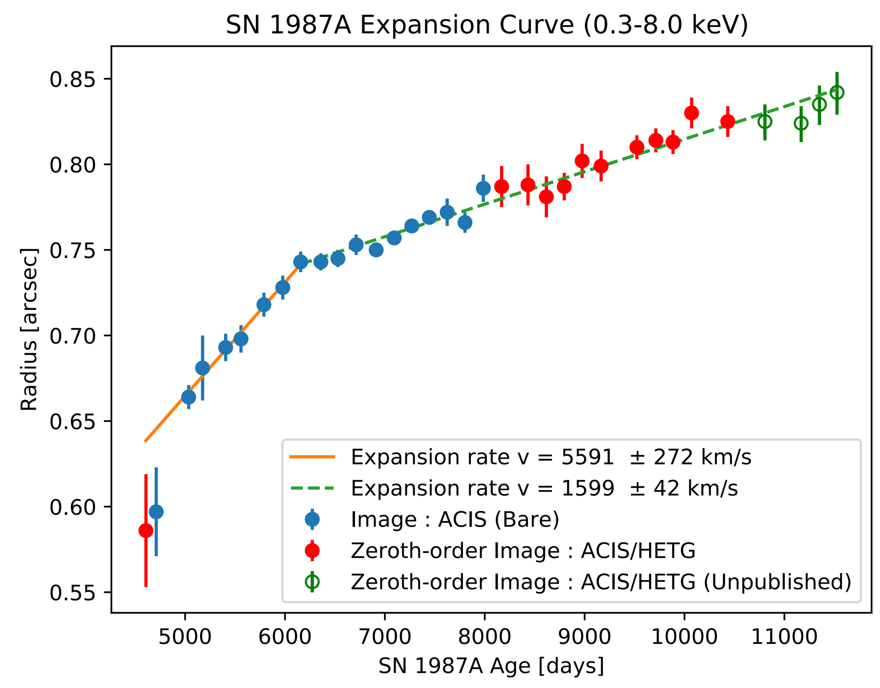

Fig 2: The 0.3-8.0 keV X-ray radius and expansion rate of SN 1987A (1999-2018). Our new updates (2016 – 2018) are show by green open circles.

Temporal Evolution of X-ray Spectrum

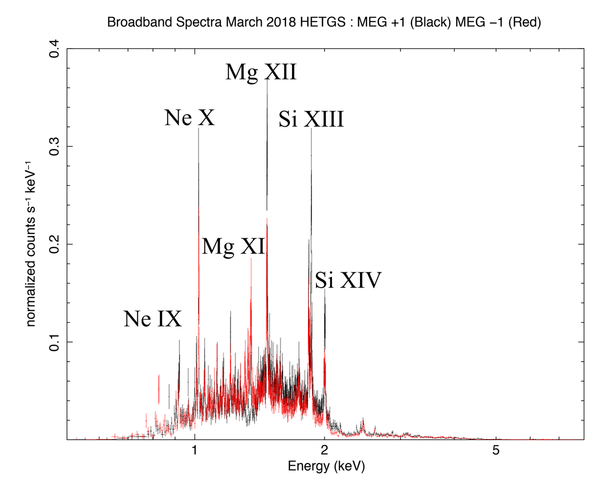

Fig 3: The 1[st] order dispersed X-ray spectrum (MEG +1 (black) MEG-1 (red)) of SN 1987A based on our 340 ks Chandra HETGS observation taken in March 2018.

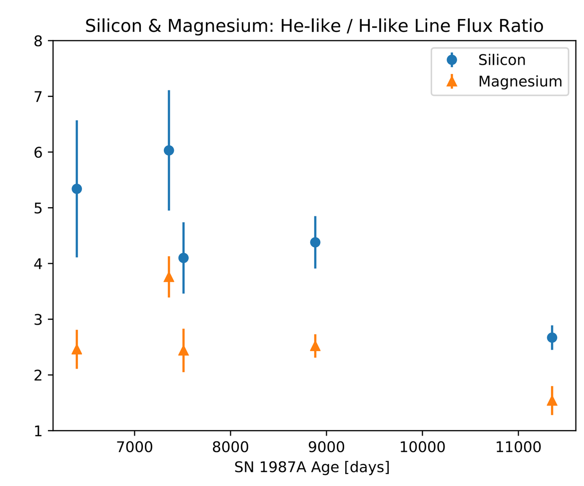

Fig 4: Temporal evolution (~ 6500 to ~ 11,300 days) of He-like / H-like ion line flux ratios of Si and Mg

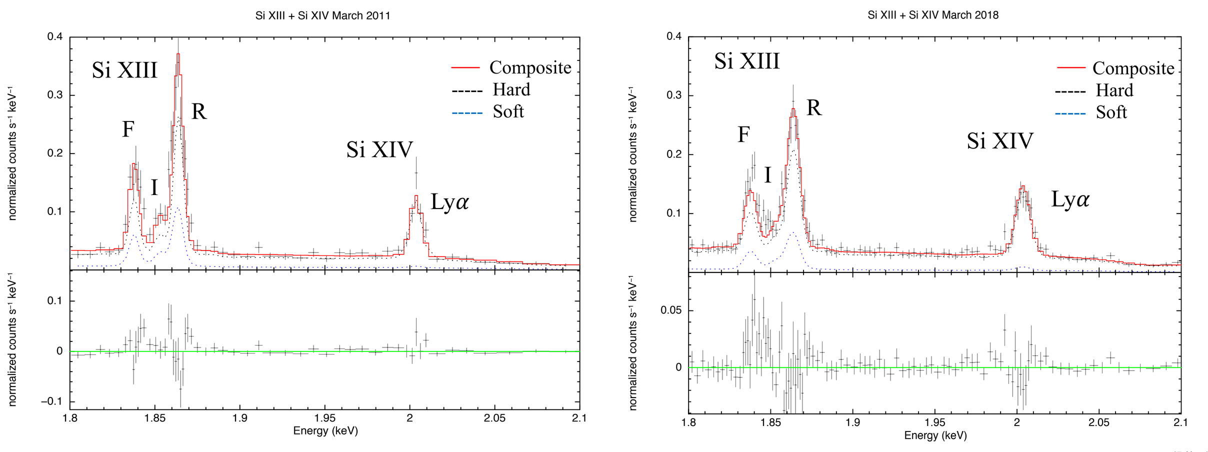

Fig 5 : 5a (Left) Si XIII and XIV lines detected in March 2011 (~ day 9000) ; 5b (Right) Si XIII and XIV lines detected in March 2018 (~day 11,300). Soft component(blue), hard component(black) and the composite two component model(red) show the models used for fitting data in 5a & 5b.

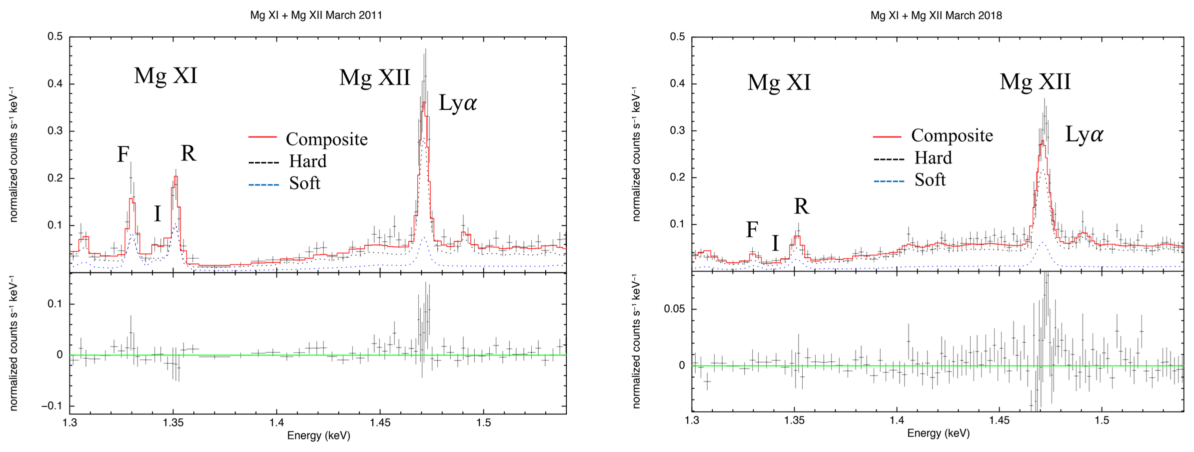

Fig 6 : 6a (Left) Mg XI and XII lines detected in March 2011 (~ day 9000) ; 6b (Right) Mg XI and XII lines detected in March 2018 (~day 11,300). Soft component(blue), hard component(black) and the composite two component model(red) show the models used for fitting data in 6a & 6b.

- Comparing our new deep HETG 1[st] order spectrum (taken in 2018, day ~11300) (Fig 3) with those extracted from the archival CXO data taken in days ~6200 (in 2004), ~7300 & 7500 (in 2007) and ~9000 (in 2011), **we find that for Si and Mg, the He-like to H-like atomic line flux ratios stayed almost constant until day ~9000 (2011) beyond which it has dropped ~ 40% by day ~11,300 (2018) [Fig 3]**. This appears to be caused by of increases in electron temperature and/or ionization timescale since day ~9000, which is inconsistent with the general trend observed until day ~9000 [eg., 9]. As we only have one data point beyond day 9000, follow-up observations from CXO can shed more light on this new trend.
- We use the same version of the two shock component NEI model as in [7] for a consistent comparison. Our initial fit results (reduced χ^2 ~ 0.7) show **no significant abundance evolution between days ~7,500 (2009) and ~11,300 (2018)**.
- Between 2011 and 2018, forbidden (F) and resonance (R) lines from the He-like triplets (eg : Si XIII & Mg XI) and the Lyα line from the H-like doublets (eg: Si XIV & Mg XII) undergo significant changes for both Si and Mg. (Figs 5 & 6). **Relative to (F) and (R) lines , the Lyα strengthens for both Si and Mg since day ~9000 (2011) which is consistent with the decreasing He-like / H-like line flux ratios (Fig 4).** At energy ranges corresponding to Si and Mg lines taken in 2018 (day ~11,300), the hard component dominates (Fig 5b & 6b). **Since day ~9000, we observe that the ionization timescale for the hard component does not increase, but the electron temperature rises from ~1.7 keV (day ~9000) to ~2.3 keV (day ~11,300)**. This suggests that increasing electron temperatures are responsible for these line profile changes.

Conclusions

- A decrease in the soft band X-ray flux and the hint for a possible rise in the radial expansion rate in our latest Chandra data may support the blast wave moving past the dense inner ring and now interacting with the less dense hitherto poorly understood circumstellar matter. These observations may be in support of recent results obtained in the optical [10] and radio bands [11]. Follow-up CXO observations are essential to monitor these intriguing developments.
- There is a significant decrease in the He-like / H-like line flux ratios for Si and Mg after 2011 (day ~9000). Broadband two component spectral model-fits suggest that increasing electron temperature between 2011 (day ~9000) and 2018 (day ~11,300) from ~1.7 keV to ~ 2.3 keV has caused significant changes in the spectral shape and could be responsible for the changing line flux ratios. Another scenario is the increasing contribution from the reverse shock moving through less dense material towards the center but we do not find clear evidence of a significant abundance increase between days ~7500 (2007) and ~11,300 (2018).
- We will perform a more detailed spectral analysis of all available deep HETG 1[st] order spectra of 87A, aided by hydrodynamic calculations [eg., 12, 13] and also adopting updated atomic data, which would help further study emergence of the shocked ejecta emission, evolution of thermal conditions, density structure, etc.