An X-ray View of SNR 1987A: Shock Evolution beyond the Inner Ring

Aravind P. Ravi[1], **Sangwook Park[1]**, Svetozar A. Zhekov[2], Salvatore Orlando[3], Marco Miceli[4], Kari A. Frank[5], David N. Burrows[6], Mikako Matsuura[7], Richard G. Arendt[8], Martha L. Boyer[9], Josefin Larsson[10], Claes Fransson[11], Armin Rest[9], Tea Temim[12]

1 University of Texas Arlington 2 Bulgarian Academy of Science 3 4 Università degli Studi di Palermo 5 Northwestern CIERA 6 PennState Eberly College of Science 7 Cardiff University Prifysgol Caerdydd 8 UMBC 9 STScI Space Telescope Science Institute 10 KTH 11 Stockholm University 12 Princeton University

Abstract

Based on our Chandra imaging-spectroscopic observations, we present the latest evolution of the X-ray remnant of SN 1987A. Recent changes in the electron temperatures and volume emission measures suggest that the blast wave in SN 1987A has started to move out of the dense inner ring structure, also called the equatorial ring (ER). The soft (0.5 – 2.0 keV) X-ray light curve shows a slight declining trend (~10%) between 2017 and 2020 as the blast wave heats the hitherto unknown circumstellar (CSM) medium outside the ER. Corresponding radial expansion rate tracing the evolution of the blast wave shows a re-acceleration, consistent with X-ray emission from less dense CSM. Since 2020, the soft X-ray flux has stabilized and the latest ACIS spectrum of SNR 1987A in 2022 shows the emerging presence of the Fe Heα line. Comparisons with the synthetic soft X-ray light curve from magnetohydrodynamic (MHD) simulations suggest an increasing contribution from the reverse-shocked outer layers of the ejecta.

Background

- SN 1987A, a core collapse supernova, was the nearest (d ~51 kpc in the LMC) and hence apparently brightest supernova observed in outburst since Kepler's supernova (1604 AD).
- Owing to its proximity, it is a unique astrophysical laboratory for the detailed study of the birth of a supernova remnant (SNR) and a neutron star.
- We study the X-ray photometric, morphological, and spectral evolution of the remnant of SN 1987A based on the excellent spatial and spectral resolutions of the Chandra X-ray Observatory (Chandra). We have been observing SN 1987A roughly every 6 months for the past 22 years (total 45 observations as of September 2022) as part of our Chandra monitoring program [e.g., 1, 2, 3, 7, 9, 12]
- X-ray flux from SN 1987A has been dominated by the shock interaction with the dense ER. The soft X-ray flux increased as the shock approached and heated the dense clumpy circumstellar medium of the ER at ~5000 days since the explosion (~2002) [2]. As the shock entered the main body of the ER at around 2004 (~6200 days since SN), the soft X-ray light curve showed a sharp upturn (**Fig. 1**) [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 ER as suggested by the soft X-ray light curve. From 2004 to 2016 (~10,500 days) this rate has stayed a constant at ~1600 km/s [12].
- A two-component non-equilibrium ionization shock model (vpshock) was used to fit the high-resolution spectra from deep grating observations between 2004 and 2018 [4, 5, 6, 8, 22]. Best-fit chemical abundances of the X-ray emitting gas (2004 – 2018) were consistent with those of the ER (Ne~0.3, Mg~0.2, Si~0.3, S~0.4, and Fe~0.2 solar) [22].
- Increasing best-fit electron temperatures (by ~40% between 2011 and 2018) and changing volume emission measures, EM ~ t^5 (between 2004 and 2011) to EM ~ $1/t^2$ (in 2011 - 2018) of the X-ray emitting gas suggested that sometime between 2011 and 2018, the blast wave in SN 1987A started moving out of the dense ER and heating the progenitor winds of the red supergiant phase [22].
- In this work, we present the latest evolution of SN 1987A based on our continuing Chandra monitoring as of September 2022. We present the observed X-ray light curves, radial expansion rate of the blast wave, and comparisons between observed and synthetic soft X-ray light curves. We also compare our latest Chandra results in Sep 2022 with the JWST NIRCam images (Filters: F150W, F164N, and F212N) of SN 1987A [23].

Results

X-ray Light Curves & Expansion Rate

- We find that the soft X-ray flux declines (by ~10%) between 2017 and 2020 (**Fig. 1**). This decreasing trend is generally consistent with the XMM-Newton results [21], and the evolving trends of electron temperatures and volume emission measures as the blast wave moves out of the dense ER and heats the low-density CSM beyond it [22].
- Since 2020, this flux has stayed relatively constant instead of declining further (**Fig. 1**). An intriguing interpretation is the increasing contribution of the X-ray emission from the reverse-shocked ejecta, as predicted by MHD simulations [16].
- The hard (3.0 – 8.0 keV) X-ray light curve continues to increase linearly, and it appears to be leveling off since ~2020 (but we need further observations to verify it).

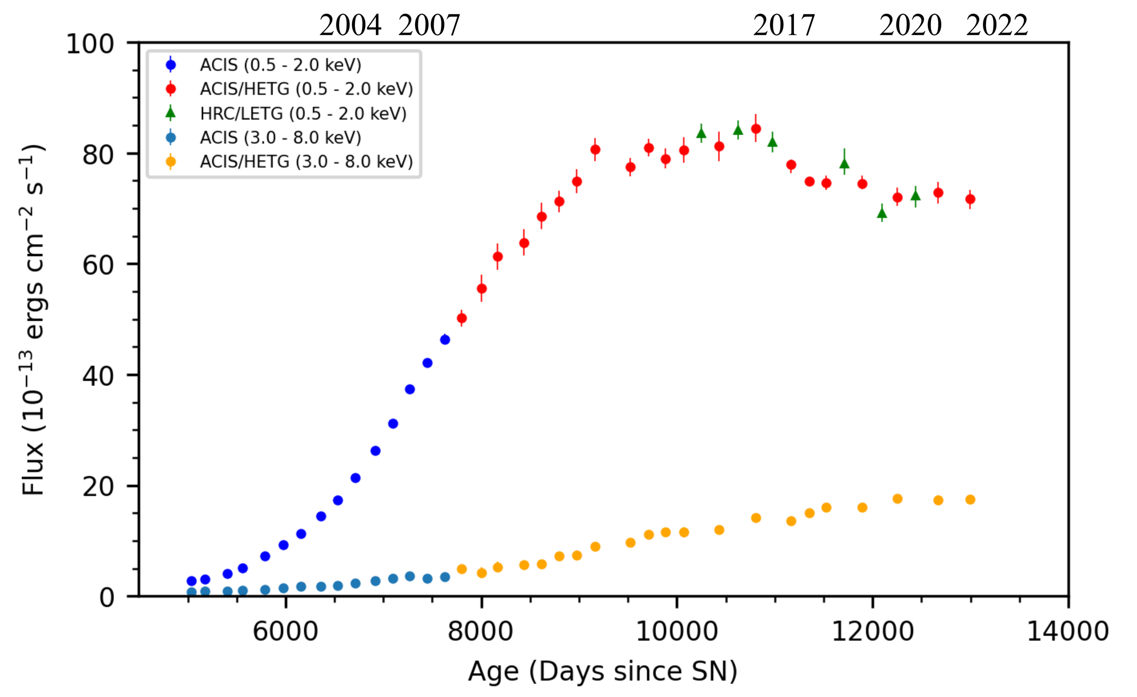

Fig. 1: Soft (0.5 - 2.0 keV, upper plot) and hard (3.0 – 8.0 keV, lower plot) X-ray light curves of SNR 1987A. The decreasing trend in soft X-ray fluxes between 2017 and 2020 appears to be stabilized since ~2020.

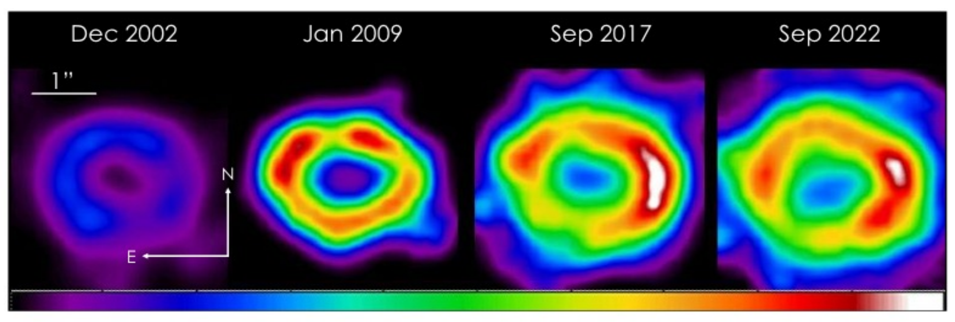

Fig. 2: The 0.3-8 keV band images of SNR 1987A at four representative epochs, based on our Chandra monitoring observations. Images are PSF-deconvolved, smoothed, and flux-normalized. The X-ray remnant has undergone significant morphological changes over the last two decades.

- While the peak of X-ray emission might still be within the ER, we approximate the outer boundary of the blast wave as a combination of the radial distance of the peak emission (r_0) and half-width of the measured thickness ($\sigma_0/2$) of the X-ray emitting ring (**Fig 2**). σ_0 of the X-ray emitting ring has increased by ~40% between ~2016 and ~2022 (previously constant ~0.2 arcsec between 2004 and 2016), causing the difference between peak emission and outer boundary expansion rates since ~2016.
- Based on our preliminary analysis, by ~2018, the outer boundary has started to expand faster (~4000 km/s), than the expansion rate of the emission peak of the ER (~1600 km/s) (**Fig. 3**). We note that while the origin of X-ray and radio emission can be different, a similar re-acceleration of the remnant was also noted in the radio band [13]. Similarly, at optical wavelengths, HST images showed emergence of significant emission outside of the ER since ~2018 [15].

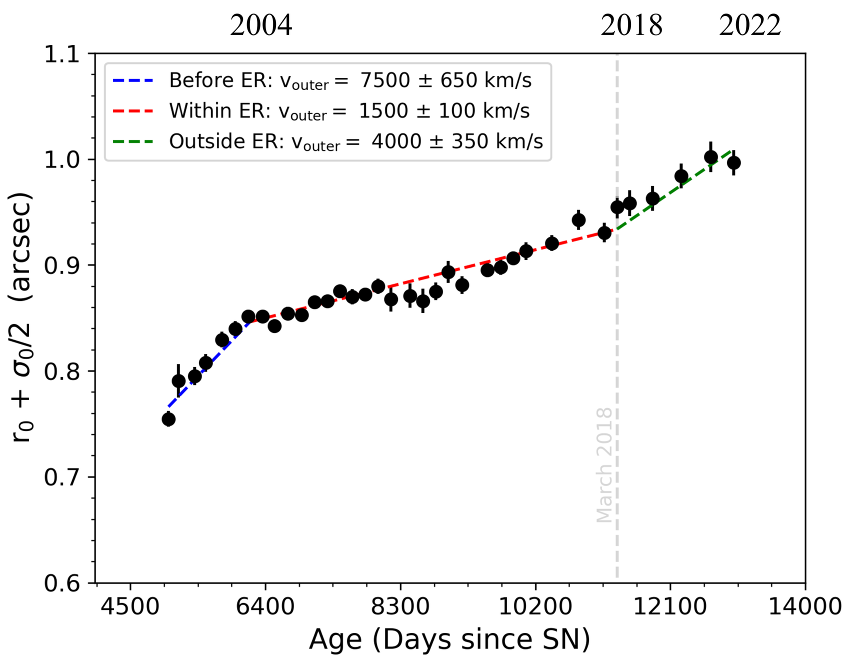

Fig. 3: Radial expansion rate of SNR 1987A based on the broadband (0.3 – 8.0 keV) Chandra ACIS images. r_0 is the measured radius of the peak intensity of the X-ray ring and σ_0 is the thickness of the ring. Since ~2017-2018, the overall expansion rate has increased.

Increasing X-ray emission from the reverse-shocked ejecta?

- Chandra ACIS spectrum in 2022 shows the clear emergence of Fe Heα line (**Fig. 4**). The best-fit two component shock model with abundances fixed at ER values [22] underestimates the observed Fe line flux. Our preliminary spectral analysis shows that an elevated Fe abundance (by ~2 times above the ER abundance of ~0.2 solar) may be required to fit the observed Fe line flux.
- At a similar epoch, the JWST NIRCam high-resolution images (**Fig. 5**) show that the [Fe II] ejecta (Filter: F164N) is now approaching the ER and inner shock-like features appear inside ER [23]. Similarly, the JWST NIRSpec data show recent brightening of Fe-rich ejecta near northern and southern boundaries of the cold central ejecta nebula [24]. These JWST observations suggest that interactions between the reverse shock and the ejecta near the ER (**Fig. 5**) might have recently started to result in some contribution in the latest observed X-ray spectrum of SNR 1987A.
- In **Fig. 6**, we show that the 3D MHD model-predicted 0.5 – 2.0 keV light curve (constrained based on observations before ~2016) is in excellent agreement with the observed soft X-ray light curve after 2016. These models predict that the X-ray emission from the reverse-shocked ejecta will be significant ≥ 2022 (i.e., ≥ 35 yr after the SN).

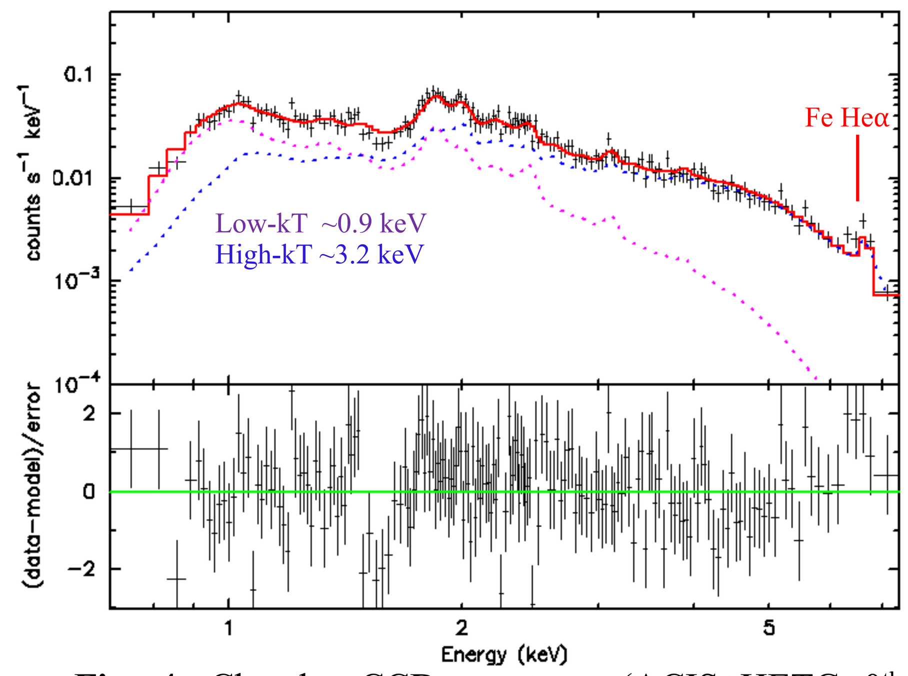

Fig. 4: Chandra CCD spectrum (ACIS+HETG 0[th] order) of SNR 1987A in September 2022. Fe Heα feature is marked. Two-component vpshock (low-kT: magenta; high-kT: blue; total: red) best-fit model at ER abundances underestimates the Fe Heα line [22].

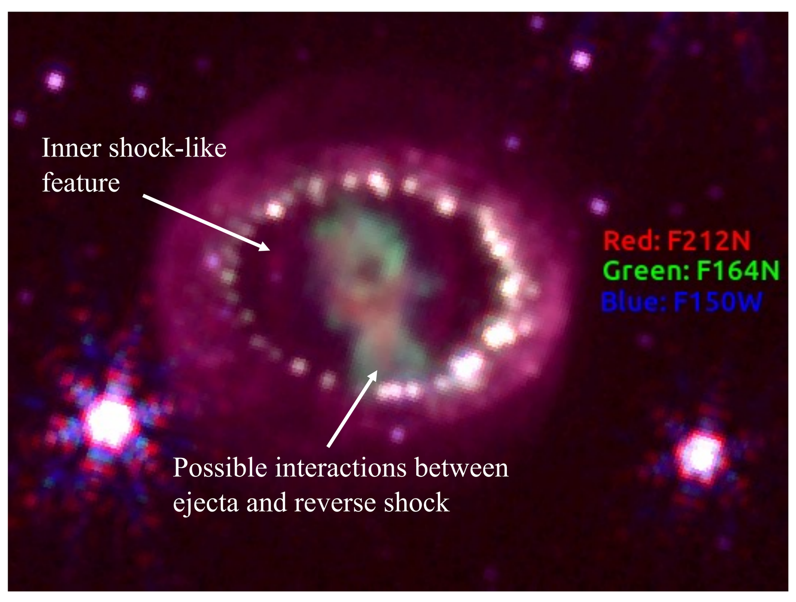

Fig. 5: 3-color JWST NIRCam image of SN 1987A (Red: F212N; Green: F164N; Blue: F150W) [23]. F164N shows the strong [Fe II] line emission.

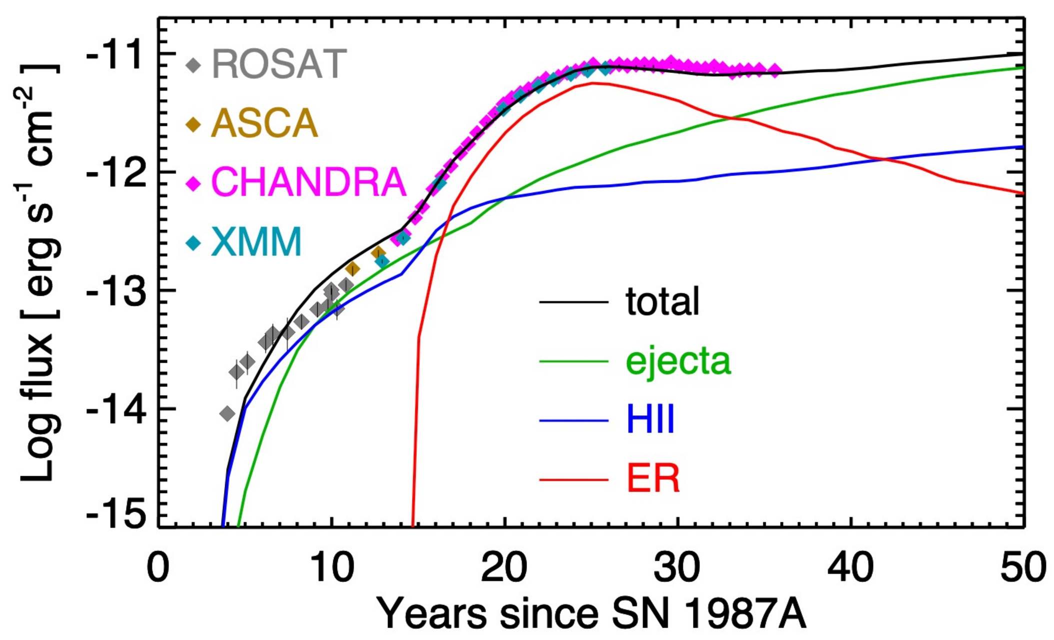

Fig. 6: Comparison between observed soft X-ray light curve and MHD-simulated model components. The model ejecta component (green) becomes significant over the model ER contribution (red) around 2022 (~35 yr) [16].

References

[1] Burrows et al. 2000 ApJ, 543L, L149.
[2] Park et al. 2004, ApJ, 610, 275.
[3] Park et al. 2005, ApJ 634L,L73
[4] Zhekov et al. 2005, ApJ, 628L, L127.
[5] Zhekov et al. 2006, ApJ, 645, 293.
[6] Dewey et al. 2008, ApJ, 676, 131
[7] Racusin et al. 2009, ApJ, 703, 1752.
[8] Zhekov et al. 2009, ApJ, 691,1190.
[9] Park et al. 2011, ApJ, 733L, L35.
[10] Dewey et al. 2011 ApJ, 752, 103
[11] Fransson et al. 2015, ApJ, 806L, 19F
[12] Frank et al. 2016, ApJ, 829,40.
[13] Cendes et al. 2018, ApJ, 867, 1.
[14] Esposito et al. 2018, ApJ, 857, 58
[15] Larsson et al. 2019, ApJ, 886, 147
[16] Orlando et al. 2020, A&A, 636A, 22
[17] Arendt et al. 2020, ApJ, 890, 2A
[18] Bray et al. 2020, 899, 21B
[19] Page et al. 2020, ApJ, 898, 125
[20] Greco et al. 2021, ApJL, 908, L45
[21] Sun et al. 2021, ApJ, 916, 41
[22] Ravi et al. 2021, ApJ, 922, 140
[23] Matsuura et al. 2022, First Science Results from JWST, Dec 12-14, 2022, Baltimore, MD
[24] Larsson et al. 2023, arXiv:2302.03576

This work has been supported in part by NASA Chandra Grants, GO7-18060A, GO8-19057X, GO8-19043B, GO9-20051B, GO2-23037X, and JWST Grant, GO-01726.032-A.

Conclusions

- Between 2011 and 2018, X-ray emitting shocks started to move out of the dense ER. Soft X-ray flux declined by ~10% between 2017 and 2020, and the outer boundary of the X-ray emitting ring re-accelerates after 2018 as the blast wave propagates into the low-density CSM beyond the ER.
- Broadband images (0.3 – 8.0 keV) do not yet show emission from the putative central neutron star which is consistent with the model-predicted high foreground absorption (≥ 10^{23} cm^{-2}) due to the central cold ejecta at these energies [14, 19, 20].
- Since 2020, the soft X-ray flux has stopped declining and appears to have levelled-off. Chandra monitoring spectrum in 2022 shows the clear emergence of Fe Heα (at E ~6.5 keV) line suggesting an increase in the Fe abundance associated with the high-kT shock component. Additionally, observations with JWST (NIRSpec and NIRCam) hint that the reverse shock interaction with the central metal-rich ejecta might have been just started.
- These latest developments in SNR 1987A may signal the onset of the reverse shock interaction with the central ejecta which may shortly cause dramatic changes in the X-ray spectrum and will be crucial to study the nucleosynthesis of SN 1987A's progenitor and its explosion physics.