Differential Emission Measure Analysis of the X-ray Gas in SN 1987A from 2007 to 2021: The Fading Ring & The Brightening Ejecta

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I. Introduction

SN 1987A is the nearest supernova (SN) observed since Kepler's SN of 1604, and one of the few supernova remnants (SNRs) for which people have performed detailed 3D MHD simulations tracing their long-term evolution from the explosion all the way to the SNR phase (e.g., Orlando+20). However, previous X-ray study results based on discrete temperature modeling (2-T/3-T, e.g., Sun+21, Greco+22) cannot be well compared with the simulation-predicted continuous gas distributions.

In order to better connect the observations with the simulations, we carried out a differential emission measure (DEM) analysis on SN 1987A, aiming at the continuous temperature distribution of the X-ray gas.

II. Data & Method

We constructed a DEM model to fit the XMM-Newton EPIC-pn + RGS spectra of SN 1987A taken from 2007 to 2021.
The EM is described as:

$$EM = \int n_e n_H dV = \int \phi(T) dT = \int T\phi(T) d(\ln T)$$

, where the DEM function $\phi(T)$ is parameterized by a 7-order Chebyshev series in 40 temperature bins (T_i, $i = 1,2,\ldots,40$) logarithmically spaced in 0.1 to 10 keV. For each T_i, the X-ray spectrum is calculated by a single `vnei` model. In order to keep the model as simple as possible, we assumed that the ionization parameter is a power-law function of the temperature: $\tau = \tau_1(\frac{T}{1\mathrm{keV}})^{\beta}$, where τ_1 is the ionization parameter at 1 keV.

III. DEM Fitting Results

The X-ray plasma in SN 1987A show a temperature distribution containing a major peak at ~0.6-1 keV and a tail extending up to ≥ 5 keV (the third row in Figure 1)..

The total EM of the major peak kept climbing in the first few years, reached its maximum at ~2011-2014, and then started to decline. On the other hand, the total EM of the tail continuously increases and seems to has formed a secondary peak at ~3-5 keV in the recent few years.

The DEM results show good consistency with the MHD simulations (the second row in Figure 1), in all following aspects: the temperature and emission measure of the major peak, the existence of a high-temperature tail and its extent, and the temporal evolution.

By comparing observations with simulations, we argue that the recent decline of the major peak and the rapid rising of the tail (the emergence of a secondary peak) reveals the fading of the ER and the brightening of the shocked ejecta.

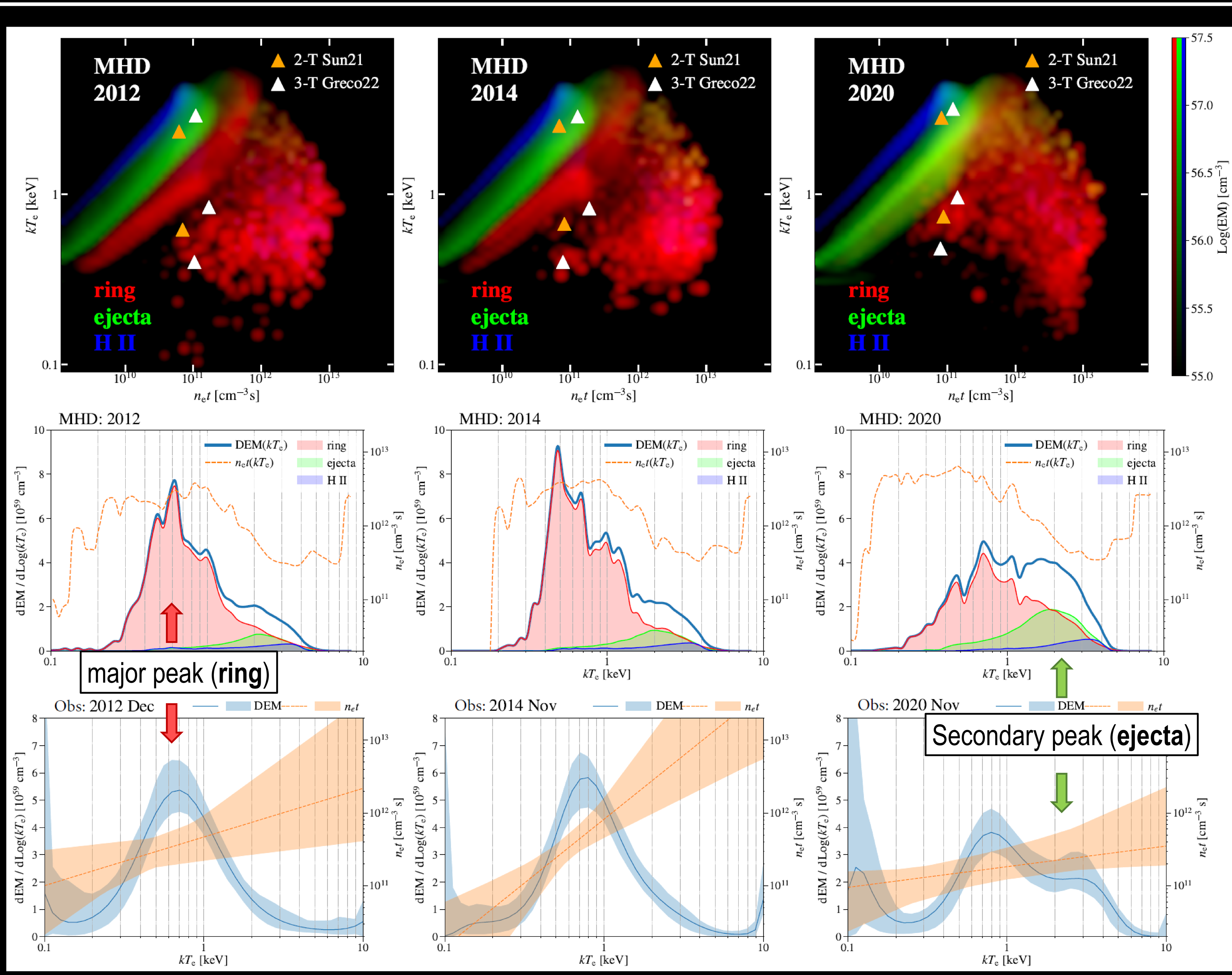

Figure 1. Comparison between MHD simulations (Orlando+20) and DEM fitting results. *Top*: simulated EM distribution in kT_e-$n_e t$ parameter space. *Middle*: simulated DEM distributions (blue solid lines) and EM-weighted $n_e t$ distributions (orange dashed lines). *Bottom*: DEM fitting results based on XMM-Newton observations.

IV. Recent Decline of Fe K Centroid Energy

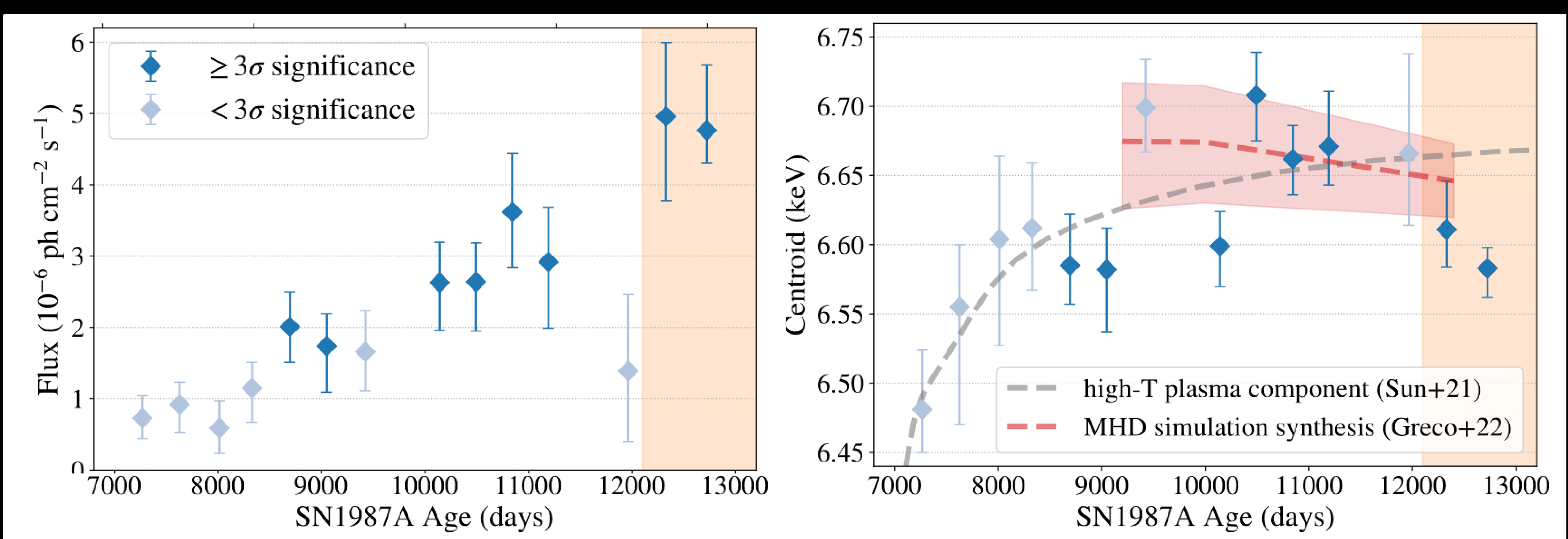

Figure 2. The flux and centroid energy of Fe K line in SN 1987A. Orange regions highlight the new results. Points with ≥ 3σ detection are shown in dark blue, while others in light blue. The gray dashed curve is adopted from Sun+2021, which represents the Fe K centroid energy for a high-temperature plasma component with kT_e~3.2 keV and $n_e = 500\ \mathrm{cm}^{-3}$, shocked at 7000 days after the explosion. The red dashed curve indicates the MHD simulation results containing the contribution of the newly shocked ejecta, obtained by fitting the synthetic spectra evaluated by Greco+2022.

We found a dramatic decline of the centroid energy of Fe K line from ~6.65-6.7 keV to ≤ 6.6 keV in the recent few years (see the right panel in Figure 2), evidencing a decrease in the average ionization level of Fe in SN 1987A. This is consistent with MHD simulations which predict the Fe K emission to be more and more contributed by the newly-shocked outer-layer ejecta with a lower ionization parameter, and thus provides an ***additional evidence for the brightening of the outermost layers of ejecta***.

References: Greco, E. et al. 2022, ApJ, 931, 132
Orlando, S. et al. 2020, A&A, 636, A22
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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