Six years of luminous X-ray emission from the strongly interacting type-Ib SN 2014C captured by Chandra and NuSTAR

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ABSTRACT

We present the first coordinated soft and hard 0.3-80 keV X-ray campaign of the extragalactic supernova SN 2014C in the first \( \sim 2307 \) d of its evolution. SN 2014C initially appeared to be an ordinary type Ib explosion but evolved into a strongly-interacting hydrogen-rich type IIn SN over \( \sim 1 \) yr. We observed signatures of interaction with a dense medium across the X-ray spectrum, which revealed the presence of a \( \sim 1 - 2 M_\odot \) shell of material at \( \sim 6 \times 10^{16} \) cm from the progenitor. This finding challenges current understanding of hydrogen-poor core-collapse progenitor evolution. Potential scenarios to interpret these observations include (i) the ejection of the hydrogen envelope by the progenitor star in the centuries prior to the explosion; (ii) interaction of the fast Wolf-Rayet (WR) star wind with the slow, dense wind of the Red Super Giant (RSG) phase, with an anomalously short WR phase.

Keywords: supernovae: specific (SN 2014C)

INTRODUCTION

SN 2014C evolved spectroscopically from a type Ib to a type IIn supernova (SN) as a result of the shock interaction with a H-rich circumstellar material (CSM) shell (Milisavljevic et al. 2015). The presence of a dense H-rich medium in close proximity to a H-poor core-collapse SN has been inferred in a number of cases, including normal type Ib/Ic SNe (e.g., 2001em, 2004dk, Chugai & Chevalier 2006; Mauerhan et al. 2018) and superluminous SNe (e.g., iPTF13ehe, iPTF15esb, iPTF16bad, Yan et al. 2017). This phenomenology might require enhanced mass-loss \( \lesssim 2000 \) yrs before explosion due to physical mechanisms that deviate from the traditional picture of line-driven winds in single massive stars (e.g. wave-driven mass-loss, envelope ejections driven by nuclear burning instabilities or binary interaction), or, alternatively, unusually short WR phases of evolution (e.g., Smith 2014).

Here we update the analysis of Margutti et al. (2017) and present new broad-band X-ray observations of SN 2014C up to \( t = 2307 \) d post explosion, enabling unprecedented insight into time-dependent mass-loss mechanisms. We study these mechanisms by using the SN shockwave as a probe of the environment as described in Chevalier & Fransson (2017).

OBSERVATIONS AND ANALYSIS

We observed SN 2014C with Chandra and NuSTAR at \( t = 396 - 2307 \) d past explosion (December 30th 2013) as part of our joint monitoring program. Each Chandra observation was paired with a NuSTAR observation taken within \( \Delta t/t < 10^{-3} \) to provide a complete view of the hard and soft X-ray emission. We reprocessed the Chandra and NuSTAR data following standard procedures within CIAO and NuSTARDAS. We find evidence for bright X-ray emission in each of our exposures both at soft and hard X-rays energies.

For Chandra observations, we extracted a spectrum from a circular region of 1.5" centered at the location of SN 2014C. We followed a similar procedure for NuSTAR exposures, but used a 1" region. We performed a joint spectral fit of each CXO+NuSTAR observation with an absorbed thermal bremsstrahlung model (tbabs*ztbabs*brems).
Figure 1. Chandra (black circles) and NuSTAR (magenta squares) broadband (0.5-40 keV) X-ray spectra of SN 2014C acquired at $t = 396 - 2307$ d post explosion. Thick blue line: best fitting absorbed bremsstrahlung model. Black rectangles: excess of emission with respect to this model that we associate with $K\alpha$ line transitions in H-like or He-like Fe atoms.

within XSPEC. We accounted for contamination from unrelated sources inside the NuSTAR PSF following a similar method as Margutti et al. (2017). NuSTAR observations are heavily dominated by background emission at energies $> 40$ keV and we thus restricted our spectral analysis to the 3-40 keV range. We adopted a Galactic neutral hydrogen column density $N_{H_{MW}} = 6.14 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005) in the direction of SN 2014C and a distance of 14.7 Mpc (Freedman et al. 2001).

DISCUSSION AND CONCLUSIONS

A SN shock expanding into the CSM accelerates particles that cool down in the X-rays by radiating synchrotron and bremsstrahlung emission (Chevalier & Fransson 2017). For shocks propagating in high-density media, like in SN 2014C, thermal bremsstrahlung emission dominates over the synchrotron in X-rays. The observed thermal bremsstrahlung spectrum depends on the emission temperature $T$, (which directly probes the shock velocity) and on the electron density of the radiating medium (and hence on the overall density $\rho$). Additionally, the presence of dense local neutral matter can lead to photo-electric absorption that leaves a clear imprint at energies $\lesssim 1$ keV (Fig. 1). We quantify the local absorption with an intrinsic column density $N_{H_{int}}$. By fitting the thermal bremsstrahlung spectra of SN 2014C over $\sim 6$ yrs of evolution, we constrained $T(t)$, $N_{H_{int}}(t)$, and the density profile encountered by the blastwave $\rho(r)$.

We find $kT$ peaks at $\sim 23$ keV at $t \sim 500$ d, and cools as $T(t) \propto t^{-0.5}$. $N_{H_{int}}$ also declines with time as the shock propagates through the dense CSM shell. Specifically, we find $N_{H_{int}}(t) \propto t^{-1.4}$ starting from $\approx 3 \times 10^{22}$ cm$^{-2}$ at $t \sim 400$ d. The resulting unabsorbed broad-band 0.3-100 keV X-ray light-curve peaks at $L_x \approx 5.5 \times 10^{49}$ erg s$^{-1}$ at $t \sim 1000$ d, followed by $L_x(t) \propto t^{-1}$, which is significantly less steep than what is expected from adiabatic expansion. Finally, we note the presence of an excess of emission at $\sim 6.7$ keV (Fig. 1) that we interpret as emission from H-like or He-like Fe atoms.

Combining the spectral parameters inferred above with direct measurements of the forward shock radius obtained from VLBI observations of SN 2014C by Bietenholz et al. (2017) and Bietenholz et al., (submitted), we constrain the properties of its environment. We find that the progenitor star is surrounded by a low-density cavity (particle density $n < 100$ cm$^{-3}$, Margutti et al. 2017) extending to $\sim 6 \times 10^{16}$ cm. At $\sim 6 \times 10^{16}$ cm, the blastwave encountered a dense shell of material with density $n \sim 2 \times 10^6$ cm$^{-3}$ extending to at least $8 \times 10^{16}$ cm and with a density profile beyond
the shell $\rho(r) \propto r^{-2.5}$. Our observations sample the medium out to $r \sim 2.5 \times 10^{17}$ cm. Under the assumption of spherical symmetry supported by recent VLBI observations of Bietenholz et al. (submitted) (see however Milisavljevic et al. 2015), the total shell mass is $\sim 1 - 2 M_\odot$ considering realistic filling factors.

Optical spectroscopy (Milisavljevic et al. 2015) indicates the CSM shell is H-rich, but it is unclear how this CSM shell was produced at such close distances from the explosion site. Viable scenarios fall under two broad categories. A first class of models does not require erratic mass-loss. Rather, the observed CSM shell is the product of the interaction of a fast wind with a slow dense wind from the previous phase of stellar evolution, e.g. the transition from RSG to the WR phase (a known mechanism able to produce “bubbles” around Galactic WRs at typical distances $\sim$ tens of pc; significantly larger than our inferred shell radius, e.g., Marston 1997). As a result, the phenomenology of SN 2014C does require an anomalously short WR phase of $\lesssim 1700$ yrs.

A second class of models invoke the ejection of the progenitor’s H-rich envelope as a result of various mechanisms including binary interaction (Margutti et al. 2017; Sun et al. 2020 for the specific case of SN 2014C), wave-driven mass-loss (Quataert & Shiode 2012; Shiode & Quataert 2014; Fuller 2017; Fuller & Ro 2018; Wu & Fuller 2020), or nuclear burning instabilities similar to those during O and Ne burning phases (Arnett & Meakin 2011; Shiode et al. 2013; Smith & Arnett 2014).

Studies of statistical samples of SN 2014C-like events across the electromagnetic spectrum hold the key to constraining the physics of the most spectacular mass-loss histories of evolved massive stars.

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