Honing In: Constraining Core-Collapse Progenitors with Chandra

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SUPERNOVAE are among the most energetic events in the universe, and one of few astronomical events which have a history dating back to the onset of human civilization. Although the general picture of how supernovae (SN) evolve is agreed upon, surprisingly little is known about their progenitor systems. This is because supernovae occupy a unique region of interdisciplinary physics bordering the rather complicated (and rapidly advancing) fields of magneto-hydrodynamics, rare nuclear physics, and advanced neutrino physics; all of which are important to their astrophysical evolution. Nevertheless, through spectral and temporal analysis spanning the entire electromagnetic spectrum, a census of events have allowed us to characterize them into two broad categories, each with their general physical evolution outlined in theory. Analysis of these transients have allowed for the separation of supernovae into Type I and Type II based on the absence or presence of hydrogen lines in their spectra respectively. Subcategories on both sides of the aisle indicate core-collapse scenarios in which a massive star's core collapses into a proto-neutron star or black hole upon the retiring of fusion processes. It is generally expected, and has been for a long time (Klein and Chevalier, 1978), that a shock wave will propagate outward from the core carrying an imprint of the physical characteristics of the star and providing signatures of progenitors. That is why **in this TOO proposal, we aim to observe the afterglow of X-rays triggered by supernova shock breakout** in order to more directly infer the progenitor star system in specific core-collapse events.

History and Imminence. Supernovae have been studied meticulously by *Chandra*. The observatory's long history of involvement in supernova science, due to its superior spatial and spectral resolution, has allowed for some of the most stringent constraints of supernova physics via the study of remnant systems (Badenes, 2010). Here, we attempt to learn about **progenitor systems to Type Ib, Ic, and II-b core-collapse supernovae (CCSN) via their early X-ray emission**. In Type Ib events, the core has collapsed and the emission lacks hydrogen lines, but exhibit He lines, Type Ic events show no signs of either element and finally, Type II-b shows early emission of hydrogen before quickly being stifled and leaving only He lines. We do not understand which types of stars will explode into these respective categories, but suspect that their progenitors may differ due to their spectral characteristics. Studying SNR objects do offer some guidance, however, older SNR systems tend to have interacted with their surrounding material significantly enough such that they are information-poor on this front as will be addressed later.

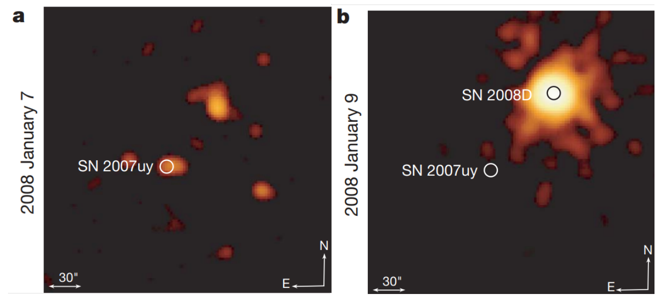

Fig. 1. Swift X-ray image of the field of SN2008D, the first reported case confirming the X-ray flash of a supernova. After 10 days, the Swift telescope was only able to give an upper limit on the X-ray flux, but Chandra was able to further resolve spatially and mask out other X-ray sources in the region, as well as obtain late-time light curve. Image adopted from (Soderberg et al., 2008)

It has long been theorized that after core-collapse, a radiation mediated shock propagates outwards into the stellar envelope. The optical thickness of the material ahead of will decrease until it's optical depth is of similar order to that of the shock transition optical depth, the radiation then escapes ahead of the shock leading to a soft X-ray/UV flash (Suzuki et al., 2016) lasting on the order of minutes, see Woosley and Weaver (1986) for a review. However, thick winds outside the stellar surface with high optical depth will suppress the flash, and - if the density of the wind does not change too rapidly - we will observe no X-ray flash (XRF), or a weaker 'wind breakout' flash. The development of the Swift telescope has allowed us to catch the first of these X-ray flashes, and have characterized them to have fast rise and exponential decay on a timescale of minutes, sometimes mimicking the signal of a typical long GRB (Nakar et al., 2010). Triggering off such an event, would allow for a fast response from Chandra to follow up on these observations and monitor them as they fall below Swift's detection threshold, see Fig. 4. As will be explored in this proposal, fitting spectra of the X-ray emission can help allow for distinguishing between progenitor systems.

Core Collapse Progenitors

Core-collapse Supernovae and X-ray Flash. Of the core-collapse kinds, Type II supernovae are expected to have evolved from red or blue supergiant stars. However, the lack of H lines in Type Ib/Ic supernova indicate that the star has lost its hydrogen envelope during late stage development. All core collapse models predict a shock breakout pulse in the extreme UV/soft X-ray, the first electromagnetic supernova observable. It may be possible that tracing the SN shock via it's X-ray emission would allow us to probe the immediate stellar environment surrounding the star, as has been suggested for SN Type Ia (Dimitriadis et al., 2014), precisely what we plan

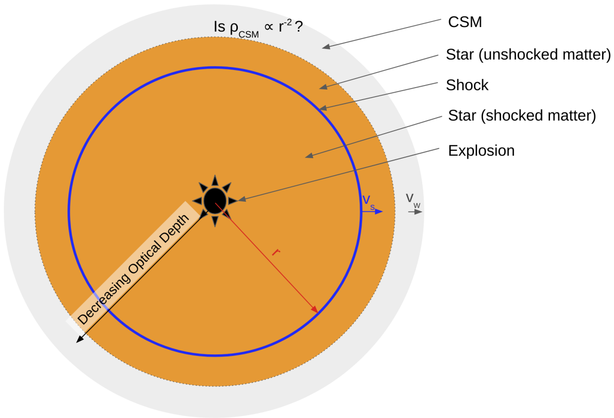

Fig. 2. Sketch of shock propagation in early stages of supernova explosion. Here v_s is the shock velocity and v_w is the wind velocity, CSM is circumstellar material.

to do in this campaign for CCSN.

One of the hypotheses explaining the missing lines in Type Ib/Ic events is dense mass loss by steady wind in the late stages of evolutionary development. We can predict how the breakout mechanism will change as outlined in (Chevalier and Irwin, 2011); as the radiation-mediated shock propagates out to the stellar surface, it will encounter a steep change in density causing the subsequent a pulse of X-rays of duration determined by R_*/c. By light-crossing time arguments, one can determine the size of the source (Calzavara and Matzner, 2004). For red supergiants, sizes of up to 10^{14} cm (Schawinski et al., 2008) will corresponds to a breakout pulse of duration approximately one hour long. However, the situation changes when a thick (and dense) stellar wind surrounds the star. In this situation, the breakout pulse duration would be dependent on R_w. In this way, the breakout flash can be used to constrain the wind+star's effective size. However, there is an implicit assumption in this analysis which is to say that the wind was emitted steadily. In this way, $R_w = R_* + v_w \cdot t_w$ where v_w and t_w are the velocity and age of the wind respectively, see Fig. 2 for a sketch of this process.

Nevertheless, early studies of X-ray flashes have indicated source radii smaller than that of typical red and blue supergiants, closer to expected Wolf-Rayet star radii (Couch et al., 2011). The steady wind assumption has been used by (Grasberg and Nadyozhin, 1987; Ofek et al., 2010) and theoretically explored in (Moriya and Tominaga, 2012), however, if the wind is not emitted steadily, then the X-ray flash would be shorter, owing to the earlier drop in mass density and optical depth and we may expect further, fainter, emission coming from the shock interacting with older winds further away from the star, providing for hardened spectra at later times, in analogy to the hard X-ray emission regions in older SNR systems due to shock acceleration and heated material, see Fig. 3, where the blue traces out the shock.

An alternative scenario considers High Mass X-ray Binary (HMXB) systems as progenitors of these hydrogen-lacking CCSN (Heikkilä et al., 2016). In this case, a heavy star is shedding mass (via winds or Roche lobe overflow) to a compact companion which exhibits accompanied X-ray emission, both prior and proceeding the explosion. It is possible - though unlikely, that such an object had been previously detected by Chandra and comparisons before and after breakout would be invaluable to this study. If undetected previously, Chandra may still be able to disentangle this scenario from the previous one: as time goes one, we expect that the power law component that would arise from shock acceleration would fade into the hard thermal spectrum typical of HMXB accretion.

Limitations of Previous Work

We begin with the Swift discovery of SN2008D in the galaxy NGC 2770, hereinafter our quintessential example of a trigger for this campaign. This was the first confirmed exhibition of supernova shock breakout detection in the X-ray. The XRF lasted a duration of 600 s, which did manage to provide limits on source size. Additionally, Chandra ObsID 9104 was independently observing NGC 2770 at the time, and managed to catch SN2008D in its field of view 10 days after the explosion. This of course, was extremely fortunate. The Chandra observations managed to place constraints on the objects X-ray luminosity and showed that it was indeed fading. If the model proposed by (Modjaz et al., 2009) is correct (see Fig. 4), it's persistent soft X-ray emission should remain stable enough for further observations by Chandra in later months, whilst out of Swift's reach. In the rest of this section, we will use SN2008D to outline the limitations of the previous Chandra, and propose solutions in order to overcome them. We note that, this is not the fault of the previous observers, D. Pooley et al., who could not have planned for this event to happen in their FOV.

A Shallow Observation. A 17.9 ks ACIS-S3 detection provided just enough information for modest spectra to be obtained, and many groups have drawn different conclusions on which model (combinations of powerlaw and blackbody fits) would fit best to the data and make the most astrophysical sense (Soderberg et al., 2008; Li, 2008; Suzuki and Shigeyama, 2010), see (Ohtani et al., 2018) for a review. Thus we reach our first qualm, the exposure was not deep enough for the source. 10 counts was too low in order to obtain good enough spectra to characterize the source fully.

Just One Look. ObsID 9104 was one 18 ks exposure of NGC 2770. It is expected that, in the steady wind model, the star loses its mass in the last few years of its life. For (high) stellar wind velocities (Rochowicz and Niedzielski, 1995), and post-breakout shock velocities of $\approx 10^3 - 10^4$ kms^{-1}, we would expect the emission in 18 ks to probe a region with a characteristic dimension of order $10^{12} - 10^{13}$ cm. If the wind emission had occurred in pulsations over the course of years, then we would expect shock interactions with these older pulses of material to be further away across a region size of order 10^{15} cm. Thus, in any single 18 ks observation we would not expect X-ray variability at all as this emission would be probing up to 1% of the total thickness of the winds, as was seen in a simple light curve on SN2008D from

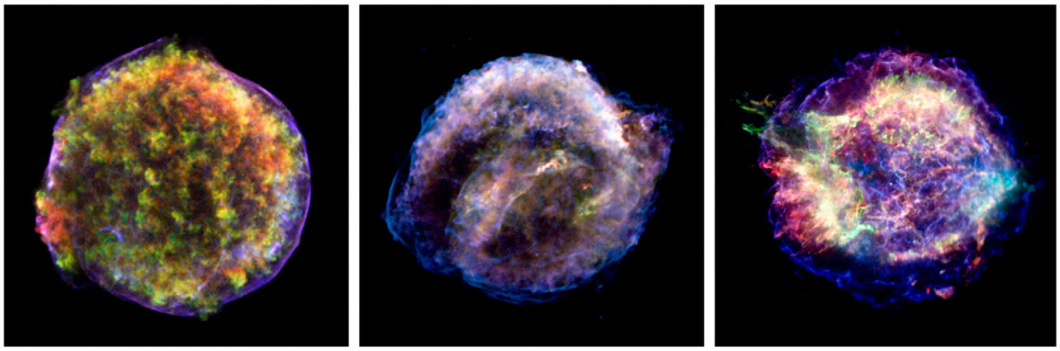

Fig. 3. False colour images of Tycho's (left), Keppler's (middle), and Cas A. (right) SNRs. Images not to scale. Total exposure times are 150, 750 and 1000 ks respectively. In all three images red is soft X-ray (below 1 keV), green is mid-energy, and blue is the 4-6 keV band. Note, the 4-6 keV band traces out the location of the shock due to heated material. Figure adopted from (Badenes, 2010) with data originally published in (Warren et al., 2005; Reynolds et al., 2007; Hwang et al., 2004), respectively.

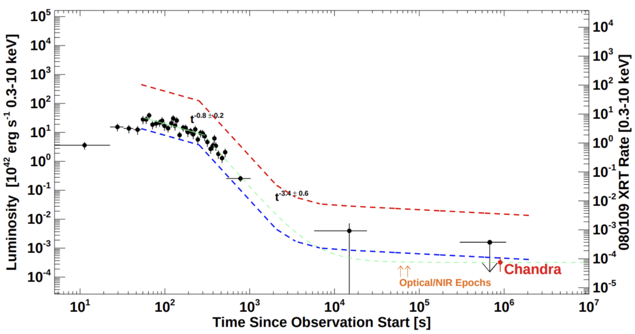

Fig. 4. X-ray light curve of SN2008D. Red dashed line corresponds to the same event happening at 70 Mpc and the blue dashed line accounts for greatly enhanced hydrogen column densities an order of magnitude higher than those in actuality. Image adapted from Modjaz et al. (2009).

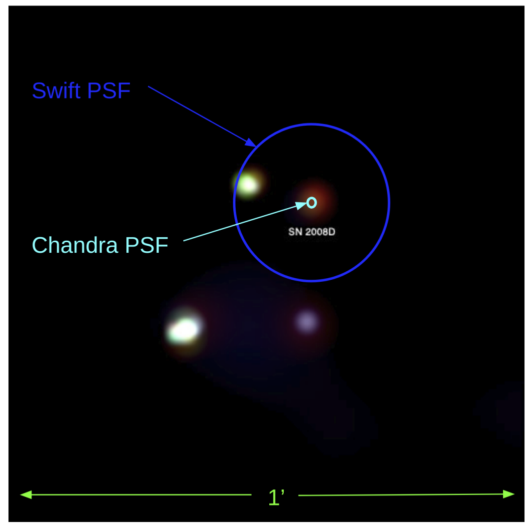

Fig. 5. Idealized PSF (not corrected for off-axis aberrations) for Chandra and Swift X-ray telescopes superposed on Chandra ObsID 9104 18 ks exposure of SN 2008D. Note that the Swift PSF does include other sources in the field which would significantly interfere with analysis. Image credit NASA/CXC/Wisconsin/D.Pooley et al.

Chandra ObsID 9104, see Fig. 6. Additionally, studies have indicated that the passage of the shock should heat the matter sufficiently to create X-rays (Katz et al., 2010), i.e. the more the shock interacts with surrounding material, the harder we would expect the spectrum. In ObsID 9104, only a modest power law spectrum was obtained and it exhibited softer emission, see Fig. 6. 10 days was just not long enough to wait in order for the shock to interact with a sufficient amount of material outside of the star for this effect to be noticeable.

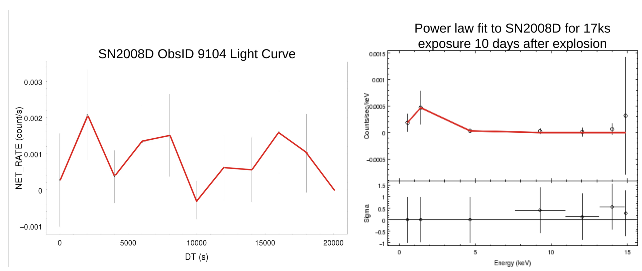

Fig. 6. Light curve and spectrum (power law fit) to ObsID9104 SN2008D X-ray emission taken 10 days after initial Swift detection.We note here that there does not seem to be any obvious variability in the light curve, additionally the exposure was not deep enough to obtain a solid spectrum. Both black body and power law fits gave poor χ_ν < 0.6, with the power law converging to slightly better values. Region was taken to be a 4" circle around the fitted position of SN2008D from (Li and Filippenko, 2008)

The Chandra Edge

Source Contamination. Both the HMXB and steady wind models require spectra to be uncontaminated in order for a thorough characterization of the source. For a typical HMXB, a harder thermal spectrum would be expected with kT > 15 keV. Other sources in the field would contaminate the observation too much, as was the case for the Swift detection of SN2008D, see Fig. 5. Since core-collapse supernovae are expected to come from massive short-lived stars, they are expected to occur in star forming regions of galaxies. Unfortunately, this is also where binary candidates, including HMXBs are likely to be found contaminating the image. Exploiting Chandra's ≈1" PSF versus Swift's ≈ 18" PSF will help to mitigate this issue significantly, as less sources will be muddied together in an image.

Planned Observations and Feasibility

We request five × 20 ks observations spread over the course of a year, making for a total of 100 ks on ACIS-S3. This would allow for proper monitoring of early shock interaction with the surrounding environment, as well as a deep enough view in order to obtain sufficient counts for evolving spectra.

The Trigger. We will trigger on a Swift XRF detected within a radius of 70 Mpc, a quarter the distance to SN2008D. This would correspond to a flux increase, of about 16 times (assuming similar event properties). If the model proposed in Modjaz et al. (2009) is correct (Fig. 4), we would expect to be able to observe the source with Chandra for the full duration of the year.

Source Count Estimates. We calculate an energy flux from ObsID 9104 using srcflux on CAIO, we then plug this into PIMMS after adjusting for now upper limit of 70 Mpc. We obtain about 70 counts per observation for each 20 ks viewing of the source. We also varied the hydrogen column density (n_H) by an order of magnitude and noted a count rate difference of a factor of 4. In either case, our worst-case scenario will provide more counts than ObsID 9104, sufficient for a good spectrum fit. The repeated observations over the course of the year would allow us to probe effective wind radii up to 10% of the full extent of the winds, hopefully allowing us to prove or dispute the steady winds approximations used by many. PIMMS allowed us to calculate a <4% pileup for sources even an order of magnitude closer at distances < 7 Mpc using the full ACIS-S3 chip. Thus, we do not consider pileup from these faint sources.

Rates & Constraints. Taking the volumetric core collapse supernova rate to be $1.04{\pm}0.19{\times}10^{-4}(h/0.7)^3 yr^{-1} Mpc^{-3}$ (Taylor et al., 2014) we obtain roughly 400 CCSN events in our trigger volume per year. Then also taking Type Ib/Ic rates to be < 25% of all CCSN events (Sadler and Campbell-Wilson, 1997). We consider a trigger to be a Swift-detected XRF lasting longer than 100 s (thus excluding stars of smaller radii and/or no winds) with peak Swift XRT rate > 1 cts/s corresponding to our 70 Mpc cut and accounting for extreme levels nH absorption. We estimate that number of events meeting these cuts and being detected by Swift to be less than a hand full per year.

If an observation fails to notice variability in the source, we have provided evidence against the description of a collisionless shock, and X-ray hardening developing 100's of days post-XRF as described by (Svirski et al., 2012; Katz et al., 2011). We would have also validated the steady wind approximation up to ≈10% of R_w and provided claims against the HMXB candidacy as a Type Ib/Ic progenitor due to missing hard X-ray component from HMXB accretion.

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