Superluminous X-ray emission from the interaction of supernova ejecta with dense circumstellar shells

The Harvard community has made this article openly available. Please share how this access benefits you. Your story matters.

Citation
Pan, Tony, Daniel Patnaude, and Abraham Loeb. 2013. “Superluminous X-Ray Emission from the Interaction of Supernova Ejecta with Dense Circumstellar Shells.” Monthly Notices of the Royal Astronomical Society 433 (1): 838–48. https://doi.org/10.1093/mnras/stt780.

Citable link
http://nrs.harvard.edu/urn-3:HUL.InstRepos:41412110

Terms of Use
This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA
Superluminous X-ray emission from the interaction of supernova ejecta with dense circumstellar shells

Tony Pan, Daniel Patnaude and Abraham Loeb

Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Accepted 2013 May 1. Received 2013 April 27; in original form 2013 March 27

ABSTRACT

For supernova (SN) powered by the conversion of kinetic energy into radiation due to the interactions of the ejecta with a dense circumstellar shell, we show that there could be X-ray analogues of optically superluminous SNe with comparable luminosities and energetics. We consider X-ray emission from the forward shock of SN ejecta colliding into an optically thin circumstellar material (CSM) shell, derive simple expressions for the X-ray luminosity as a function of the circumstellar shell characteristics, and discuss the different regimes in which the shock will be radiative or adiabatic, and whether the emission will be dominated by free–free radiation or line cooling. We find that even with normal SN explosion energies of \(10^{51}\) erg, there exist CSM shell configurations that can liberate a large fraction of the explosion energy in X-rays, producing unabsorbed X-ray luminosities approaching \(10^{44}\) erg s\(^{-1}\) events lasting a few months, or even \(10^{45}\) erg s\(^{-1}\) flashes lasting days. Although the large column density of the circumstellar shell can absorb most of the flux from the initial shock, the most luminous events produce hard X-rays that are less susceptible to photoelectric absorption, and can counteract such losses by completely ionizing the intervening material. Regardless, once the shock traverses the entire circumstellar shell, the full luminosity could be available to observers.

Key words: shock waves – circumstellar matter – supernovae: general – stars: winds, outflows – X-rays: general.

1 INTRODUCTION

An interesting question is whether there could be X-ray counterparts to superluminous supernovae (SNe), with comparable luminosities and/ or total energy emitted. Excluding the energy emitted by neutrinos, most core collapse SNe have explosion energies of the order of \(10^{51}\) erg, but usually only \(10^{49}\) erg of that energy is released as optical radiation during the SN, with typical peak luminosities not exceeding \(\sim 10^{43}\) erg s\(^{-1}\). However, numerous superluminous SNe with luminosities \(\gtrsim 10^{44}\) erg s\(^{-1}\) were discovered over the past decade (Gal-Yam 2012), some of which had total radiated energies \(\sim 10^{51}\) erg, e.g. SN 2003ma (Rest et al. 2011) and SN 2006tf (Smith et al. 2008). Although a few of these events may be powered via radioactive decay, e.g. the candidate pair-instability supernova SN 2007bi (Gal-Yam et al. 2009), a distinct majority of superluminous SNe require some other mechanism to power their radiative output.

One of the main mechanisms\(^1\) invoked to convert a larger fraction of the explosion energies into optical emission is via the strong interaction between the expanding SN ejecta and massive circumstellar material (CSM) previously expelled by the star (Smith & McCray 2007). Similarly to Type IIn SN, the bulk kinetic energy of the ejecta is converted back into radiation via strong shocks (Chevalier & Fransson 1994). The energetics of this process can be understood via the following toy model: if two objects of mass \(M_a\), \(M_b\) with velocities \(v_a, v_b\) collide and stick together, conservation of energy and momentum dictates that the kinetic energy lost from the inelastic collision will be

\[
\Delta E_{\text{kinetic}} = \frac{1}{2} \frac{M_a M_b}{M_a + M_b} (v_a - v_b)^2. \tag{1}
\]

If \(v_b \gg v_a\), and the lost kinetic energy is converted to radiation with efficiency \(\alpha\), then the total radiated energy will be

\[
E_{\text{rad}} \approx \alpha \frac{M_b}{M_a + M_b} E_a, \tag{2}
\]

where \(E_a\) is the kinetic energy of mass \(M_a\).

For the CSM interaction scenario, where \(M_a\) is the SN ejecta and \(M_b\) is the circumstellar shell, this approximation is valid since an SN ejecta’s velocity typically reaches \(10^3\) km s\(^{-1}\) while mass previously ejected by stars has velocities ranging from \(\sim 10^3\) to \(10^4\) km s\(^{-1}\). Also, \(E_a \sim 10^{51}\) erg is approximately the total energy of the SN.

\(^1\)The other main mechanism is the outward diffusion of deposited shock energy in optically thick CSM, i.e. the shock breakout, which can also produce X-rays; see Section 6.

* E-mail: span@physics.harvard.edu

© 2013 The Authors
Published by Oxford University Press on behalf of the Royal Astronomical Society
as adiabatic expansion quickly converts the initial deposited energy of the SN into kinetic form. The radiative conversion efficiency is typically high, $\alpha \gtrsim 0.3$–0.5, at least for optical radiation from thermalized shock material (Ginzburg & Balberg 2012; Moriya et al. 2013). Thus, from equation (2), for a given total system mass and explosion energy, the energy radiated away is linearly proportional to the CSM mass $M_b$. So although most SN only radiate 1 per cent of their total kinetic energy, a large circumstellar mass $M_b$ can substantially recover the SN energy lost by adiabatic expansion. Notably, in this toy model, the total radiated energy does not depend on the location of the circumstellar mass $M_b$.

Several mechanisms may eject a large mass from the star prior to its death as an SN. For example, luminous blue variables (LBVs) are evolved, unstable massive stars, and giant eruptions from LBVs result in dramatically increased mass-loss and luminosity, some of which are so extreme that they are initially mistaken for SN. These SN impostors are powerful but non-terminal eruptions (i.e. not core collapse); however, there is direct evidence linking at least some LBVs and SN impostors to actual SN: e.g. SN 2006jc (Foley et al. 2007), in which the progenitor star is observed to violently erupt only two years before its terminal explosion; other examples include SN 2005gl (Gal-Yam et al. 2007; Gal-Yam & Leonard 2009) and possibly SN 2009ip (Mauerhan et al. 2013). Alternatively, some of the most massive stars with helium core masses between $\sim 40$–60 $M_\odot$ encounter core instability from the softening of the equation of state due to the production of electron–positron pairs, which results in explosive burning that is insufficient to fully unbind the star, but can result in a sequence of SN-like eruptions of shells of matter shortly before the star dies. The collision of subsequent shells of ejecta can also produce a superluminous SN, i.e. the pulsational pair-instability SNe (Heger & Woosley 2002; Woosley, Blinnikov & Heger 2007; Chatzopoulos & Wheeler 2012). Also, the tunnelling of wave energy from the core (driven by fusion-luminosity-induced convection) into the stellar envelope can lead to extremely large stellar mass-loss rates a few years prior to core collapse (Quataert & Shiode 2012). Alternatively, the collective action of winds at different evolutionary stages of the progenitor star can form wind-blown cavities, bordered by a thin, dense, cold shell constituting material swept up by the winds; the emission of SNe in these wind-blown bubbles has been examined (Chevalier & Liang 1989; Dwarkadas 2005).

Now, for CSM-interaction-powered SN, the generation of optical emission requires that high densities are still maintained when the SN ejecta collides with the CSM, usually implying that the CSM is relatively near to the star ($\lesssim 10^{15}$ cm). However, the physical mechanism behind LBV outbursts is not yet known, so there is little theoretical constraint on the timing between the outburst and the SN afterwards; observational constraints so far set the lower limit to 40 d (Ofek et al. 2013a), but the delay can be years to decades or longer (Davidsson & Humphreys 2012). As for the pulsational pair-instability mechanism, the interval between pulses can be anywhere from $\sim 1$ week to $> 1000$ yr (Woosley et al. 2007). As longer delay times between eruptions imply that subsequent ejecta takes longer to catch up to previous ejecta, it is quite possible that the collision between ejecta can occur at larger radii. As for the CSM shells bordering wind-blown bubbles, they are naturally placed by the duration of winds during late stellar evolutionary stages (e.g. Wolf–Rayet) at least $10^{19}$–$10^{20}$ cm away from the star.

So, if instead the SN ejecta encounters a massive CSM shell at larger radii $> 10^3$ cm, the shell material is spread thinner, and depending on the CSM shell mass, the resulting shock can be optically thin, albeit still dense enough to drive strong emission. Such an event could still radiate extreme amounts of energy, perhaps comparable to the currently observed superluminous SNe, but the actual optical emission could be quite modest, with the bulk of the radiation instead emitted in X-rays.

Moreover, in this scenario the bulk of the X-ray emission may come from the forward shock, i.e. from the shocked CSM shell. This has an important advantage compared with most cases of X-ray emission from young SNe (without a CSM shell), in which the reverse shock is usually denser, and the observed emission is usually attributable to line-cooling emission from the reverse shock running in the SN ejecta, especially at later times (Chevalier & Fransson 2003). An important detriment of the cooling is that the intervening cooled, dense post-shock gas may photoelectrically absorb most of the emission from the reverse shock. However, even if the forward shock is radiative, and a cool, dense shell forms, this post-forward-shock cool gas will be behind the newly shocked CSM with respect to an observer on Earth – in contrast to the opposite arrangement for the reverse shock. Thus, for forward shock emission from SN and CSM shell interactions, only absorption and scattering by the pre-shock CSM is important, and even these go away once the forward shock runs through the CSM shell.

Chugai (1993) proposed an analogous scenario for the X-ray emission from SN 1986J, in which the emission originates from the forward shock front moving into dense wind clumps, and Chugai & Chevalier (2006) modelled the luminous X-ray emission $\sim 10^{41}$ erg s$^{-1}$ of SN 2001em as an interaction of normal SN ejecta with a dense, massive CSM shell, albeit attributing the observed luminosity to a non-radiative reverse shock. The evolution of SN ejecta expanding into a power-law density CSM has been well studied (Chevalier 1982a,b), and simple formulas for its dynamics and emission exist in terms of self-similar solutions; however, these are not applicable for a CSM shell.

In this paper, we consider the forward shock emission from SN ejecta colliding into a CSM shell, and derive simple, general formulas for: (i) the regimes in which the shock will be radiative versus non-radiative, and whether the X-ray luminosity will be powered by free–free emission or line cooling, and (ii) the approximate luminosity and total energy emitted as a function of the CSM shell mass, distance from the progenitor and thickness, as well as the SN explosion energy. We give examples of possible extremely luminous or energetic emission events.

2 CSM SHELL CHARACTERISTICS

For the range of masses expelled in LBV eruptions, there have only been two outbursts where we can directly measure the ejected mass – around $10 M_\odot$ for η Car, but only 0.1 $M_\odot$ for PCygni (Smith et al. 2011). As for pulsational pair-instability events, most pulses eject $\sim 1 M_\odot$ shells, but the full range also spans from 0.1 to $10 M_\odot$. Note that we make a distinction here between eruptive mass-loss and wind-driven mass-loss, which also occur for LBV-like progenitors of Type IIn SNe. Model-inferred wind-driven mass-loss rates of Type II SN progenitors are found to range from a few $10^{-2}$ to $10^{-1}$ $M_\odot$ yr$^{-1}$ (Kiewe et al. 2012), but smooth winds will result in an $r^{-2}$ density distribution instead of a shell, unless the wind
experiences dramatic changes in its mass-loss rate or velocity right before stellar demise. Here we consider the range of masses $M_{CS}$ of the CSM shell in the range $10^{-2} < M_{CS} < 10 M_\odot$, and define the dimensionless CSM shell mass $M_1 \equiv (M_{CS}/1 M_\odot)$.

For the range of locations for the CSM shell, we consider scenarios where the previously ejected shell of material is at a radius $R_1$ of at least $10^{15} - 10^{17}$ cm, which means that even at SN ejecta velocities of $10^3$ km s$^{-1}$, the interaction event would not happen until at least several months to several years after the progenitor star’s explosion. Here we consider the radius $R_{CS}$ of the CSM shell in the range $10^{15} < R_{CS} < 10^{19}$ cm, and define the dimensionless CSM shell radius $R_{17} \equiv (R_{CS}/10^{15}$ cm).

The thickness of the CSM shell is affected by the duration of the mass-loss episode. For many models of episodic mass-loss from massive stars, these eruptions occur for 1–10 years every $10^3–10^4$ years, and lose a total of 0.1–10 $M_\odot$ per episode. Note that if the mass-loss is smooth during the episode, as in the super-Eddington steady-state continuum-driven wind through a porous medium (Shaviv 2000; Owocki, Gayley & Shaviv 2004), then if the heighted mass-loss lasts 1–10 years with speed 100 km s$^{-1}$, the shell thickness is $3 \times 10^{14} - 3 \times 10^3$ cm. Alternatively, for explosive expulsions of mass, e.g., via the pulsational pair instability, due to the spread in velocities of the expelled material, the thickness of the CSM shell may be substantial compared to the radius, $\Delta R_{CS}/R_{CS} \sim 1$. Conversely, for the dense shells bordering wind-blown bubbles, the shells are typically thin $\Delta R_{CS}/R_{CS} \sim 10^{-2}$. Here we consider the range of thicknesses $\Delta R_{CS}$ of the CSM shell in the range $10^{13} < \Delta R_{CS} < 10^{17}$ cm, and define the dimensionless CSM shell thickness $\Delta R_{17} \equiv (\Delta R_{CS}/10^{15}$ cm).

Assuming that the CSM shell is spherically symmetric with uniform density, the surface density of the CSM shell is given by

$$
\Sigma_{CS} = 1.6 \times 10^{-2} M_1 R_{17}^{-2} \text{ g cm}^{-2}.
$$

(3)

The density of the CSM shell will depend on the thickness of the shell, $\rho_{CS} = \Sigma_{CS}/\Delta R_{CS}$, and so we define the electron number density of the CSM shell as

$$
n_\gamma = \frac{n_{CS}}{10^4 \text{ cm}^{-3}} = 0.95 M_1 R_{17}^{-2} \Delta R_{17}^{-1}.
$$

(4)

Note that $n_{CS} \approx 10^4$ cm$^{-3}$ corresponds to a mass density of $\rho_{CS} \approx 1.7 \times 10^{-17}$ g cm$^{-3}$. In reality, the CSM shell may be clumpy, but the clumps could be completely crushed and then mixed within the forward shock, making okay the smooth shell approximation at least for the calculation of post-shock dynamics and its X-ray emission (Chugai & Chevalier 2006).

We only consider regimes where the CSM shell is optically thin, i.e. the optical depth of the CSM shell for electron scattering $\tau = \kappa_\epsilon \Sigma_{CS}$ is less than unity:

$$
\tau = 5.4 \times 10^{-3} M_1 R_{17}^{-2} < 1.
$$

(5)

Note that this line-of-sight optical depth does not change even if the post-shock material is compressed and the density rises. Here we adopt the electron scattering opacity, $\kappa_\epsilon \approx 0.34$ cm$^2$ g$^{-1}$ at solar abundances. Once the SN ejecta collides with the CSM shell, the shock will heat up the shell material, and the temperature right behind the forward shock could reach $10^7–10^8$ K, generating 1–100 keV photons. But unlike other superluminous Type IIa SN, in the scenarios considered in this paper, as the shocked material cools and emits free–free radiation, such radiation will generally not be re-processed and thermalized by the CSM (to $T \sim 5000–20,000$ K blackbody temperatures, resulting in optical emission), but instead immediately leak away as X-rays.

### 3 Theory: Simple Formulas

#### 3.1 Shock velocity, temperature and cooling mechanism

We assume that the pre-shock CSM shell is effectively stationary, i.e. the shock velocity $v_s$ is much greater than the original velocity of the CSM shell. To find the shock velocity $v_s$, of the forward shock travelling through the CSM shell, we can write the force equation for the shocked CSM shell:

$$
\frac{d}{dt} \Sigma v_s = P(t),
$$

(6)

where $P(t)$ is the pressure interior to the CSM shell after the SN shock hits the shell, and

$$
\Sigma = \int_0^{x_s} \rho_{CS} \, dx
$$

(7)

is the surface density of matter in the shocked CSM shell, and $x_s$ is the distance that the shock has propagated into the CSM shell. If we make the approximation that the shock velocity is constant, at least within the CSM shell, then we can derive from equations (6) and (7) that $\rho_{CS} v_s^2 = P_s$; that is, the ram pressure pushing back on the shocked CSM shell moving at velocity $v_s$ (thin shell approximation) into the external, stationary CSM equals the post-shock pressure interior to the shocked CSM shell. Therefore,

$$
v_s = \left( \frac{P_s}{\rho_{CS}} \right)^{1/2}.
$$

(8)

Now, we can approximate the pressure exerted by the SN ejecta immediately before the shock hits the CSM shell as $P_{SN} = (\gamma - 1) E_{SN}/V_{SN} = E_{SN}/2 \pi R_{CS}^3$; here $V_{SN}$ is the volume interior to the shell, and we assume a $\gamma = 5/3$ gas in this paper. This assumes that the SN energy is thermalized, which is generally true if the CSM shell mass is comparable to the SN ejecta mass. For convenience, we define the dimensionless SN explosion energy $E_{31} \equiv (E_{SN}/10^{51}$ erg).

However, once the shock hits the CSM shell, the kinetic energy of the flow is converted into thermal energy, and the pressure rises above $P_{SN}$. By solving the one-dimensional non-radiative gas dynamics of a plane-parallel shock impinging on a density discontinuity, it can be shown that the immediate post-transmitted shock pressure is a factor of $\beta$ greater than the pre-transmitted shock pressure, where $\beta$ is a function of the density ratio $\rho_{CS}/\rho_0$ across the density discontinuity at the CSM shell and $\rho_0$ is the density of material interior to the CSM shell (Sgro 1975):

$$
\frac{\rho_{CS}}{\rho_0} = \frac{3A_e(4A_e - 1)}{(3A_e(4A_e - 1))^{1/2} - 5^{1/2}(A_e - 1))^{1/2}},
$$

(9)

$$
\beta = \frac{4A_e - 1}{4 - A_e}.
$$

Instead of expressing subsequent equations as a complicated function of $\rho_0$, we use the shock pressure increase factor $\beta$ to parametrize the severity of increase in density at the CSM shell; $\beta$ monotonically increases from 1 to 6, as $\rho_{CS}/\rho_0$ increases from 1 (no obstacle) to $\infty$ (solid wall), with $\beta = 2.6, 4.4, 5.4$ and 5.8 for $\rho_{CS}/\rho_0 = 10, 10^2, 10^3$ and $10^4$. The large values of $\beta$ are transitory and apply
when the shock first propagates into the denser region. Also note that the immediate post-shock density \( n_i \) increases by a factor of \( (\gamma + 1)/(\gamma - 1) = 4 \) over the pre-shock density \( n_{CS} \). Hence,

\[
v_i = \left( \frac{\beta P_{SN}}{\rho_{CS}} \right)^{1/2}.
\]

Note that this is approximately equal to another formula in literature, i.e. \( v_i \approx v_{SN} \sqrt{\rho_{SN}/\rho_{CS}} \) (Chugai 1993), where \( v_{SN} \) is the SN ejecta velocity. In this paper, we only consider the forward shock propagating in the CSM shell, but note that after the forward shock overruns the dense CSM shell, the shock will accelerate as it encounters sparser material, and can be modelled using the formalism of Dwarkadas (2005).

Thus, we can derive the dimensionless shock velocity \( v_8 \equiv (v_i/10^8 \text{ cm s}^{-1}) \) as

\[
v_8 = 1.00 \beta^{0.5} E_{51}^{0.5} M_{1}^{0.5} R_{17}^{-0.5} \Delta R_{15}^{0.5}.
\]

For a strong shock with an infinite Mach number, the conservation of mass, energy and momentum that dictates the shock velocity \( v_i \) (here \( T \approx 2[(\gamma - 1)/(\gamma + 1)] m_i v_i^2 \), where \( k \) is Boltzmann’s constant, \( \gamma \) is the adiabatic index, and \( T_i \) and \( m_i \) are the temperatures and ion masses of each plasma species. Note that if an electron–proton plasma is maximally out of thermal equilibrium, then \( T_e/T_i \sim m_e/m_p \sim 1/1836 \); clearly, whether electron–ion energy equipartition has been reached has great consequence to the electron temperature and thus the observational signature. If the plasma is in full thermal equilibrium, we can use a single temperature \( T \) to describe it, with

\[
T \approx 1.36 \times 10^3 v_8^3 \text{ K}.
\]

Here we have assumed a mean atomic weight \( \mu \approx 0.6 \) for a fully ionized plasma of solar abundance.

The time-scale for electrons and ions to reach equipartition is

\[
t_{eq} \approx 8.4 T^{3/2} n^{-1} \text{ in cgs units (Spitzer 1962)},
\]

implying

\[
t_{eq} \lesssim 10^4 v_8^3 n_7^{-1} \text{ s},
\]

where the inequality originates from the fact the post-shock density \( n_i \geq 4n_{CS} \) depending on whether the shocked gas further cools and compresses. As we shall see, for most high-luminosity cases, energy equipartition will be reached in a lot less than a day, with \( t_{eq} \) being far less than the cooling time \( t_{cool} \) or the shock traversal time through the CSM shell \( t_{flow} \), and it is mostly safe to assume that the electron temperature is the same as the temperature of the ions.

The subsequent luminosity of the shocked hot gas is driven by their mechanism of radiative cooling, captured by the cooling function \( \Lambda \). Even at solar metallicity, the cooling function is a complicated function of temperature. For simplicity, we approximate its behaviour into two regimes (Chevalier & Fransson 1994). When \( T > 4 \times 10^7 \text{ K}, \) free–free emission dominates, and \( \Lambda \approx 2.5 \times 10^{-27} T^{0.5} \text{ erg cm}^{-3} \text{ s}^{-1} \), whereas when \( 10^5 < T \lesssim 4 \times 10^7 \text{ K}, \) line emission increases, and \( \Lambda \approx 6.2 \times 10^{-10} T^{-0.6} \text{ erg cm}^{-3} \text{ s}^{-1}; \) these are rough fits to the cooling curves calculated by Raymond, Cox & Smith (1976). Hence, we can define a dimensionless cooling function \( \Lambda_{-23} = \Lambda(T)/10^{-23} \text{ erg cm}^{-3} \text{ s}^{-1} \):

\[
\Lambda_{-23} = \begin{cases} 0.92 v_8 & \text{if } v_8 > 1.7 \text{ (free–free)} \\ 3.25 v_8^{1.2} & \text{if } v_8 < 1.7 \text{ (line cooling)} \end{cases}
\]

In reality, the cooling function \( \Lambda \) is also a function of the emitted photon frequency \( \mu \), and a detailed \( \Lambda(T, \mu) \) would provide us with an emission spectrum. We utilize this more involved approach to simulations in Section 5.

### 3.2 Radiative versus non-radiative shock

A radiative shock typically forms when the density of the ambient medium is high enough, such that the emitted radiation affects the dynamics of the gas behind the shock; this occurs when the cooling time \( t_{cool} \) is shorter than the hydrodynamical time \( t_{flow} \approx \Delta R_{CS}/v_i \):

\[
t_{flow} = 0.32 \Delta R_{15} v_8^{-1} \text{ yr}.
\]

The cooling time of a gas element in a shock can be calculated as the ratio between the thermal energy density \( \epsilon = 3/2n_i kT \) and the cooling rate per unit volume \( \Lambda = n_i^{2} \Lambda \) (Franco et al. 1993):

\[
t_{cool} = \frac{\epsilon}{\Lambda} \approx \frac{3kT}{2n_i \Lambda(T)},
\]

where \( n_i \) is the immediate post-shock density. Thus, depending on the shock temperature,

\[
t_{cool} = \begin{cases} 0.24 v_8 n_7^{-1} \text{ yr} & \text{if } v_8 > 1.7 \text{ (free–free)} \\ 0.07 v_8^{1.2} n_7^{-1} \text{ yr} & \text{if } v_8 < 1.7 \text{ (line cooling)} \end{cases}
\]

Thus, the condition for a radiative shock \( t_{cool} < t_{flow} \) can be expressed as

\[
\begin{align*}
v_8^2 &< 1.31 n_7 \Delta R_{15} & \text{if } v_8 > 1.7 \text{ (free–free)} \\
v_8^2 &< 4.61 n_7 \Delta R_{15} & \text{if } v_8 < 1.7 \text{ (line cooling)}
\end{align*}
\]

We plot the dependence of these different regimes on the CSM shell mass \( M_1 \), radius \( R_{17} \) and thickness \( \Delta R_{15} \) in Figs 1 and 2, noting that the transition between regimes is much smoother than depicted.

### 3.3 Luminosity and total energy emitted

#### 3.3.1 Non-radiative shock

The X-ray luminosity of a non-radiative shock-heated plasma can be calculated as \( L = EM \times \Lambda \), where \( EM \) is the emission measure and \( \Lambda \) is the cooling function. The emission measure for the fully shocked CSM shell can be calculated as the emission volume \( V_{CS}/4 \), which is the CSM shell volume \( V_{CS} = 4\pi R_{CS}^2 \Delta R_{CS} \) compressed by the shock, multiplied by the square of the post-shock density \( n_i = 4n_{CS}, \) assuming that the density is uniform throughout. Thus, \( EM = 4.50 \times 10^{44} M_1^2 R_{17}^{-2} \Delta R_{15}^{-1} \text{ cm}^{-3} \).

Combined with the cooling rate at different shock velocities/temperatures in equation (14), we can find the non-radiative luminosity as a function of system parameters, expressed in terms of a dimensionless X-ray luminosity \( L_{42} = (L/10^{42} \text{ erg s}^{-1}) \) as follows.

When \( v_8 > 1.7 \), the luminosity of the non-radiative shock set by free–free emission (thermal bremsstrahlung) is

\[
L_{42} = 0.42 \beta^{0.5} E_{51}^{0.5} M_{1.5}^{1.5} R_{17}^{-2.5} \Delta R_{15}^{-1.5}.
\]

When \( v_8 < 1.7 \), the luminosity of the non-radiative shock set by line cooling is

\[
L_{42} = 1.46 \beta^{-0.6} E_{51}^{0.6} M_{1.6}^{2.6} R_{17}^{-1.4} \Delta R_{15}^{-1.6}.
\]

Assuming no other energy loss mechanism, we can naïvely estimate the total energy emitted as \( L_{X} t_{cool} \); however, since non-radiative shocks can have extremely long cooling times, expansion
Figure 1. Emission properties of the shock in the CSM shell, varying the shell radius $R_{17} \equiv (R_{CS}/10^{17} \text{ cm})$ and thickness $\Delta R_{15} \equiv (\Delta R_{CS}/10^{15} \text{ cm})$. The panels show different choices for the SN explosion energy $E_{51} \equiv (E_{SN}/10^{51} \text{ erg})$, shell mass $M_{1} \equiv (M_{CS}/1M_{\odot})$ and the shock pressure increase factor $\beta$ (equation 9). The red and blue regions cover where the shock is dominated by free–free emission or line cooling, respectively, in which the darker red and blue regions depict where the shock is radiative. The overlapping yellow regions show where the electron scattering optical depth along the line of sight is $\tau > 0.01$, 0.1 and 1, respectively. The dashed grey lines depict contours of constant X-ray luminosity, with the thicker line indicating where $L_{42} \equiv (L/10^{42} \text{ erg s}^{-1}) = 1$; each adjacent line towards the left is more luminous by a factor of 10. The luminosity roughly increases with $\tau$, but at $\tau > 1$ the X-rays start being reprocessed into optical emission instead; hence, $10^{44} \text{–} 10^{45} \text{ erg s}^{-1}$ is the maximum X-ray luminosity possible. Similarly, the dot–dashed green lines depict contours of constant shock temperature, with the thicker line indicating where $T = 10^{7} \text{ K}$; each adjacent line in the direction of the red region is hotter by a factor of 10. Although luminosities up to a few $10^{44} \text{ erg s}^{-1}$ are possible at $\tau \lesssim 1$, photoelectric absorption is severe (equation 27), and so except for high-temperature shocks $T \sim 10^{9} \text{ K}$ emitting many $\gtrsim 20 \text{ eV}$ photons, the full luminosity would not be observable until the shock runs through the entire CSM shell. Similarly, for $10^{44} \text{ erg s}^{-1}$ pre-absorption luminosities, the early shock emission will be completely obscured unless the temperature reaches $T \gtrsim 10^{8} \text{ K}$. For the same optical depth (i.e. column density), the highest luminosities are best reached via radiative shocks dominated by free–free emission.
of the shocked CSM shell can convert its thermal energy back into bulk kinetic form, instead of eventually emitting the energy as radiation. The shocked CSM shell expansion time-scale is roughly

$\tau_{\text{exp}} = 31.7 R_{17} v_{8}^{-1} \, \text{yr}$. \hspace{1cm} (22)

This is the time it takes for the shocked shell to double in radius, and lose half its energy via $P \, dV$ work. Therefore, we estimate the total energy released via

$E_X = L \times \min(t_{\text{cool}}, \tau_{\text{exp}})$. \hspace{1cm} (23)

### 3.3.2 Radiative shock

An important difference between a radiative shock and a non-radiative shock is that the former can increase the density drastically by a factor of $f_n \gg 4$. Immediately downstream from the shock, the Rankine–Hugoniot jump conditions are still valid, and the density has been compressed by only a factor of 4. However, as the shocked gas radiates energy away further downstream, its temperature drops precipitously, and its density increases to compensate and keep the total pressure constant. At approximately a cooling length $L_{\text{cool}} = v_{\text{cool}} t_{\text{cool}}$ away, the shocked gas condenses into a cold, dense shell; the density increase is usually limited to a factor of $\sim 100$ by magnetic pressure.

Therefore, in calculating the luminosity of a radiative shock, the emission measure will never reflect the entire shocked CSM shell volume, as material one cooling length downstream from the shock will have cooled ‘completely’ and no longer contribute X-ray emission. The emission measure can thus be approximated as the emission volume $4\pi R_{CS}^2 L_{\text{cool}}/f_n$ (accounting for compression) multiplied by the post-shock density squared $n_i^2 = f_n n_{CS}^2$. Using equation (16), and noting the average kinetic energy $3/2kT \approx 1/2m_p v_i^2$ per particle, we find that the kinetic energy of the explosion is converted to radiation at a rate:

$L = 2\pi R_{CS}^2 \rho_{CS} v_i^2$

$= 0.99 \times 10^{42} M_1 \Delta R_{15}^2 v_i^2 \, \text{erg} \, s^{-1}$, \hspace{1cm} (24)

where $\rho_{CS}$ is the pre-shock density. Hence, the luminosity of a radiative shock is

$L_{\text{rad}} = 0.99 \beta^{1.5} E_5^{1.5} M_1^{-0.5} R_{17}^{-1.5} \Delta R_{15}^{-5}$. \hspace{1cm} (25)

Note that because of occultation by the interior SN ejecta, only half of the above X-ray luminosity typically escapes to the observer. However, since the X-ray emission from the radiative forward shock will emit in all directions, i.e. both towards the observer and backwards into the cooled material behind the forward shock front, the latter cold dense material could reprocess the X-ray, resulting in concurrent optical emission.

The total energy released in X-rays can be approximated as $E_X \approx L \times t_{\text{flow}}$. However, if photoelectric absorption is severe (see the next subsection), and none of the emitted X-rays escape until the shock front reaches the end of the CSM shell, the total energy emitted observable in X-rays may only be $E_X \approx L \times t_{\text{cool}}$.

### 3.4 Scattering and absorption with the pre-shock CSM shell

We first emphasize that, after the shock runs through and superheats the entire CSM shell, many effects that decrease the transmitted X-ray flux become irrelevant, as there is no intervening material left from the initially cold CSM shell to absorb or scatter X-ray
photons. This is implicitly assumed in our luminosity formula for non-radiative shocks in equations (20) and (21), which consider the entire volume of the shocked CSM shell in the emission measure. However, it is useful to understand photon interactions with the pre-shock CSM to characterize the observable emission of the forward shock at early times as it just begins to propagate through the CSM shell.

The pre-shock column density \( N_{\text{sh}} \approx \Sigma/m_p \) of the CSM shell is given by
\[
N_{\text{sh}} \approx 9.5 \times 10^{21} M_1 R_1^2 \text{ cm}^{-2}
\]
\[
\approx 1.8 \times 10^{24} \text{ cm}^{-2}.
\] (26)

In the second equation, we express \( N_{\text{sh}} \) as a function of the electron scattering optical depth \( \tau \) (from equation 5) from an equivalent but fully ionized column, for ease of comparison via the constant \( \tau \) contours in Figs 1 and 2, even though \( N_{\text{sh}} \) refers to neutral material. So the effective cross-section for photoelectric absorption is \( \sigma(\lambda) \approx 2.2 \times 10^{-23} \lambda^{0.3} \text{ cm}^2 \) for a solar composition gas, where \( \lambda \) is the X-ray photon wavelength in units of \( \AA \). This implies that the threshold photon energy for photoelectric absorption is
\[
E(\tau_{\text{esc}} = 1) \approx 1.2 \left[ \frac{N_{\text{sh}}}{10^{23} \text{ cm}^{-2}} \right]^{1/8} \text{ keV},
\] (27)
below which we can assume that the observed spectrum is suppressed (Chevalier & Fransson 2003). Note that the dense CSM shell is likely to be fragmented and clumpy, due to Rayleigh–Taylor instabilities. For a fixed shell mass, a non-uniform, clumpy shell will typically result in less overall absorption compared with the uniform density shell we have assumed in this paper; so our inferences regarding photoelectric absorption are somewhat pessimistic. In any case, for column densities \( N_{\text{sh}} \geq 10^{24} \text{ cm}^{-2} \), X-rays <10 keV are absorbed, and one needs to observe the source at 10–100 keV. If the column density increases to \( N_{\text{sh}} \approx 10^{25} \text{ cm}^{-2} \), primary X-rays up to several tens of keV are absorbed. So in order to observe high X-ray luminosities before the shock has passed through the CSM shell, simply requiring that the optical depth \( \tau \lesssim 1 \) of the ionized CSM shell is grossly insufficient, unless the shock temperature is high \( T \sim 10^7 \text{ K} \) (\( v_0 \approx 10 \)), or that the shock luminosity itself can ionize the CSM shell.

Assuming that photoionization is determined by the current X-ray luminosity, we can define an ionization parameter \( \xi = L/nR^2 \) in cgs units (Tarter, Tucker & Salpeter 1969):
\[
\xi = 10 L_{42} M_{-1} \Delta R_{15},
\] (28)
which determines the ratio of photon flux to particle number density for a fixed temperature of the X-ray source. Typically, for shock temperatures around \( T \sim 10^8 \text{ K} \), the intermediate elements (such as C, N, O) are fully ionized when \( \xi > 10^3 \), but ionizing the heavier elements such as Fe requires \( \xi \geq 10^4 \). The medium is completely ionized once \( \xi \sim 10^4 \) (Chevalier & Irwin 2012), and there is no photoelectric absorption regardless of high column densities. These conditions are slightly modified for higher energy photons from \( T \sim 10^9 \text{ K} \) shocks, as they are more effective at ionizing atoms with higher atomic numbers.

Also, Compton scattering can affect the escape of high-energy photons, as the inelastic scattering of photons transfers energy from the photon away to the scattered electron, increasing the photon wavelength by \( \Delta \lambda \sim E \mu m_e c^2 \). Consequently, the number of scatterings is \( \sim \tau_{\text{esc}}^2 \), above a cutoff energy \( E_{\text{cut}} = \Delta E \tau_{\text{esc}}^2 \) the photon energy will be entirely depleted via Comptonization. Therefore, the cutoff energy can be approximated via \( E_{\text{cut}} \sim m_e c^2/\tau_{\text{esc}}^2 \). But since the pre-shock optical depth \( \tau_{\text{esc}} < 1 \) for the scenarios considered in this paper, most of our X-ray emission at photon energies \( \lesssim 0.5 \text{ MeV} \) will not suffer Compton degradation.

**4 POSSIBLE LUMINOUS EVENTS**

Next, we discuss possible configurations of the CSM shell that give rise to luminous X-ray emission \( \gtrsim 10^{44} \text{ erg s}^{-1} \), i.e. more luminous than any X-ray transient observed so far attributed to SN ejecta interactions with the CSM. Conservatively, we use only typical SN explosion energies of \( 10^{47} \text{ erg} \) (despite the fact that many optically superluminous SNe have been inferred to have \( >10^{42} \text{ erg} \) explosion energies), and we also assume that the post-transmitted shock pressure does not increase substantially, i.e. \( \beta \approx 1 \). In actuality, the density jump from the CSM shell interior to the shell itself can be very large, and \( \beta \approx 5–6 \) is quite possible, at least when the shock first enters the dense CSM shell; therefore, our estimates may have underestimated the maximum shock velocity by a factor of \( \beta^{0.5} \), the maximum shock temperature by a factor of \( \beta \) and the peak luminosity of radiative shocks by a factor of \( \beta^{1.5} \approx 10 \).

Generally, in our parameter space, CSM shells that give rise to the most luminous X-rays \( L \gtrsim 10^{44} \text{ erg s}^{-1} \) have radii \( R_{\text{CS}} \lesssim 10^{16} \text{ cm} \); this is because higher luminosities are reached at higher shell densities, with the largest luminosities being reached when the Thomson scattering optical depth \( \tau \) is very close to 1 but not greater. Luminosities above \( 10^{44} \text{ erg s}^{-1} \) are generally dominated by free-free emission. We give specific examples below and briefly discuss their observational signature. Note that our models assume spherical symmetry, but when the CSM shell is narrow, i.e. \( \Delta R_{\text{CS}}/R_{\text{CS}} < 1 \), or when photoelectric absorption limits detectable X-ray emission to the edge of the CSM shell, the breaking of spherical symmetry can severely reduce the luminosity calculated via our models. Fortunately, the superluminous long-duration events described in Section 4.1.1 can be found either for radiative shocks in moderately thick shells or for non-radiative shocks with very large emission volumes, for which \( \Delta R_{\text{CS}}/R_{\text{CS}} \) is not small.

**4.1 Long-duration events**

**4.1.1 Superluminous and energetic free–free emission**

In this example, the CSM shell has a mass of \( 1 M_\odot \), a radius of \( 10^{16} \text{ cm} \) and a thickness of \( 10^{16} \text{ cm} \), reaching a pre-shock density of \( 10^5 \text{ cm}^{-3} \). Electron–ion energy equipartition is reached in \( t_\text{eq} \sim 10 \) d or less, and the unabsorbed luminosity from the radiative shock attains \( \sim 10^{42} \text{ erg s}^{-1} \) for about 100 d, liberating a majority of the SN explosion energy; this is our X-ray analogue of optically superluminous SN! In this extreme case, the shock is essentially trapped in the CSM shell; the kinetic energy of the SN ejecta will be radiated away, and this infant SN remnant, less than one year of age, will go directly to the radiative phase, avoiding the Sedov phase.

The initial column density is a staggering \( 10^{24} \text{ cm}^{-2} \), which if neutral can absorb all X-rays below \( \sim 7 \text{ keV} \). However, not only does the fast \( v_0 \sim 10^8 \text{ km s}^{-1} \) shock emit photons \( \gtrsim 20 \text{ keV} \), but the large ionization parameter \( \xi \sim 10^4 \) implies that the early shock luminosity will quickly and completely ionize the remaining un-shocked CSM shell material, warding off photoelectric absorption. Therefore, the \( \sim 10^{44} \text{ erg s}^{-1} \) intrinsic luminosity will be observable for most of this event’s three-month duration.

Non-radiative shocks can generate luminous events too. For example, for a shell mass of \( 0.2 M_\odot \), a radius of \( 5 \times 10^{15} \text{ cm} \) and a
thickness of $2 \times 10^{15}$ cm, when the shock escapes the shell, a peak X-ray luminosity of $5 \times 10^{43}$ erg s$^{-1}$ is attained, after which the entire shocked CSM shell emits and cools for one month. These adiabatic shocks can have long equipartition times; here $t_{eq} \sim 9$ d is not an issue, but other luminous, non-radiative shocks could have equipartition times significantly exceeding the cooling time.

Regardless of whether the shock is radiative or not, we find that almost all superluminous (i.e. $>10^{43}$ erg s$^{-1}$) and long-duration (i.e. $\gg 1$ d) events have fast, hot shocks dominated by free–free emission. Less luminous versions have already been seen, e.g. SN 2010jl (Chandra et al. 2012b), and a candidate superluminous X-ray event, SCP 06F6, was reported after this paper was submitted (Levan et al. 2013), see Section 6.

4.1.2 Luminous line emission from radiative shocks

We consider a massive $5 \ M_{\odot}$ CSM shell with a radius of $2 \times 10^{16}$ cm and a thickness of $2 \times 10^{5}$ cm. The pre-shock density is quite high, $n_{CS} = 6 \times 10^{5}$ cm$^{-3}$, but due to the large radius, the pressure from the SN is spread over a larger area, so that the shock velocity is only $1400$ km s$^{-1}$, and thus the shock temperature $T \sim 3 \times 10^{7}$ K is much cooler than the previous superluminous examples, resulting in softer X-ray photons of a few keV. The resulting radiative shock produces a respectable pre-absorption luminosity of roughly $7 \times 10^{42}$ erg s$^{-1}$ for half a year, converting 10 per cent of the SN explosion energy into radiation. However, the column density is $10^{24}$ cm$^{-2}$ like before, but now the ionization parameter is only $\xi \sim 30$, and can only partially ionize the intermediate elements. Therefore, during most of the 160 d it takes for the radiative shock to traverse the CSM shell, the X-ray flux will suffer heavy photoelectric absorption, and we will not see a rise in luminosity until the shock nears the end of the shell, after which the shock will cool in a matter of days.

Hence, these intrinsically luminous radiative shocks dominated by line emission may have long underlying durations, but their actual observable durations are typically short.

4.1.3 Modest line emission from non-radiative shocks

In this example, the CSM shell has a mass of $0.5 \ M_{\odot}$, a radius of $2 \times 10^{15}$ cm and a thickness of $10^{15}$ cm, reaching a pre-shock density of $10^{6}$ cm$^{-3}$. The optical depth is only $\tau = 7 \times 10^{-5}$, i.e. the column density is $10^{22}$ cm$^{-2}$; this is much less than the previous examples, but the shock temperature here is only $1.4 \times 10^{5}$ K, so the X-ray emission is soft, and much of it will still be absorbed. Therefore, the peak luminosity of $9 \times 10^{40}$ erg s$^{-1}$ will not be observable until the shock traverses the entire shell. However, it takes for the shocked shell material over half a year to cool, so the shocked CSM shell will emit for this length of time even after the shock has left the shell, making it easily observable.

4.2 Short-duration events

4.2.1 Superluminous flares?

If the CSM shell has a mass of $0.05 \ M_{\odot}$, a radius of $2 \times 10^{15}$ cm and a thickness of $10^{14}$ cm, reaching a pre-shock density of $10^{10}$ cm$^{-3}$, the X-ray luminosity from the resulting shock reaches a staggering $5 \times 10^{42}$ erg s$^{-1}$, but only lasts for 1 d, liberating $\sim 5$ per cent of the SN explosion energy. The shock velocity reaches $10^{8}$ km s$^{-1}$, and $t_{eq}$ is only 1/10 the duration of this event, so electron temperatures of $10^{9}$ K will be reached rapidly; this proposed class of events will generally produce extremely hard X-rays with a Bremsstrahlung spectrum.

In reality, the spherical symmetry of the CSM shell is likely to be broken. For instance, if the radius of the CSM shell at different locations varies by a factor of 2, the emission would be spread over a month, reaching less extreme luminosities of $\sim 10^{41}$ erg s$^{-1}$.

4.2.2 Luminous cool flares?

It is possible for a radiative shock to generate a luminous X-ray flare powered by line emission, albeit at lower luminosities than before. For example, consider a CSM shell with mass $0.2 \ M_{\odot}$, radius $2 \times 10^{16}$ cm and thickness $10^{14}$ cm; the pre-shock density is still high $10^{9}$ cm$^{-3}$, but the shock velocity is only $1600$ km s$^{-1}$, resulting in a characteristic photon energy of only $\sim 3$ keV. The luminosity reached for these events can be $\sim 10^{41}$ erg s$^{-1}$; however, the column density is typically large $\gg 5 \times 10^{22}$ cm$^{-2}$, with the ionization parameter $\xi < 10^{3}$ insufficient to ionize the unshocked shell material. Hence, the full luminosity can be observed for only a few days, when the shock reaches the end of the CSM shell.

5 SIMULATION

To investigate the time evolution of the SN shock interacting with the ejected circumstellar shell, we performed hydrodynamical simulations including a time-dependent ionization calculation. The simulated systems were chosen to have luminous, adiabatic shocks in the CSM shell, where strong radiative cooling is not important for the hydrodynamics. We employed the numerical hydrodynamics code VH-1 (e.g. Blondin & Lundqvist 1993) using the non-equilibrium ionization calculation similar to that discussed in Patnaude, Ellison & Slane (2009) but without the diffusive shock acceleration calculation.

The SN ejecta is modelled as a power law in velocity ($v_{ej} \propto v^{-\alpha}$) with a flat inner density profile (Truelove & McKee 1999), which interacts with a circumstellar wind within the CSM shell. Except for one model, the SN ejecta mass is set at $4 \ M_{\odot}$, the explosion energy is $2 \times 10^{50}$ erg, the ejecta power-law index is $\alpha = 3$, and the CSM shells span a range of masses ($0.1–1.0 \ M_{\odot}$) and thicknesses ($10^{14}$–$10^{15}$ cm), with a fixed CSM shell radius of $10^{16}$ cm. The circumstellar wind is derived from a progenitor mass-loss rate of $M = 2 \times 10^{-5} \ M_{\odot}$ yr$^{-1}$ with a wind velocity of $10$ km s$^{-1}$. Shells at distances much greater than $10^{16}$ cm would produce X-ray emission at later times than considered here. The simulation models the interaction between 10 d and 0.8 yr after the SN. The upper limit on the time-scale allows for the shock to fully traverse the CSM shell.

We compute the 0.5–30.0 keV thermal X-ray emission as a function of time to compare against the results depicted in Figs 1 and 2, as well as some of the adiabatic shock scenarios described in Section 4. We plot the unabsorbed and absorbed luminosity versus time for several models in Fig. 3. Models where the total radiated X-ray luminosity exceeds the SN kinetic energy were discarded; these models have strong radiative shocks, outside the regime of validity for our simulation code.

The luminosities seen in Fig. 3 are in general agreement with the predictions from the simple theory of Section 3, although the peak luminosity of the simulations can exceed the predicted luminosity by a factor of $\sim 5$. The discrepancy is most likely due to the fact that the CSM shell mass in these simulations was small compared with the SN ejecta mass, and so the SN energy may not be thermalized.
inside the CSM shell at the time of impact, but thermalization is assumed in our simple analytical models of Section 3. The shock velocity in the shell declines slowly with time in the numerical simulations, which support the assumption of constant shock velocity in our analytical model. As shown in Fig. 3, luminous X-ray emission with $L_X \approx 10^{42} - 10^{44}$ erg s$^{-1}$ is attained once the blastwave hits the shell. Most models show a fast rise in emission once the blastwave impacts the shell, followed by a slow decline.

The superluminous non-radiative shock discussed in the third paragraph of Section 4.1.1 is also plotted in Fig. 3. Compared with the other simulated systems, here a lower mass CSM shell is placed closer to the star, but the shell is thicker. This results in a longer rise time in emission (once the blastwave hits the shell, at around 0.15 yr). This model also contains half the explosion energy as the other models, and the blastwave transits across the shell for a longer period of time.

Our model also computes the detailed thermal X-ray emission out to 30 keV. In Fig. 4, we show the X-ray emission at the point when the shocks break out of the circumstellar shells. The overall normalization, spectral lines and line ratios differ significantly between these two models. The shape of the underlying continua also shows differences, particularly above 10 keV where the model with the thicker shell shows a steeper spectrum at high energies (though appears flatter than the model with the thin shell at low energies). While the spectral resolution and throughput of current X-ray observatories may not be able to discriminate between these models, high-spectral-resolution missions such as Astro-H may be able to.

6 DISCUSSION

Our simple formulas are in rough agreement with other predictions in the literature. Adapting our formulas with a filling factor for clouds in the wind-blown CSM of SN 1986J (Chugai 1993), we arrive at similar luminosities and shock temperatures as observed.

For SN 1987A, our model agrees exactly with the luminosity $L = 4 \times 10^{38}$ erg s$^{-1}$ predicted by Chevalier & Liang (1989) for the collision of the SN 1987A's ejecta with its circumstellar ring (with $M_1 = 0.1$, $R_{17} = 5$, $\Delta R_{15} = 1.6$), but only $L \sim 10^{35}$ erg s$^{-1}$ was actually observed (Burrows et al. 2000), probably due to the drastic difference between the spherical geometry of our models and the
shape of the ring. As for possible superluminous X-rays from SN CSM interactions, Terlevich et al. (1992) studied the interaction of SN with a uniform circumstellar medium of \( n \sim 10^7 \, \text{cm}^{-3} \) as the basis of a starburst model for active galactic nuclei, and found that the SN quickly becomes strongly radiative, with most of the X-ray emission coming from the forward shock, which may reach a bolometric luminosity of \( 10^{43} \, \text{erg s}^{-1} \), consistent with our findings for CSM shells.

Among the most luminous X-ray SNe ever detected includes SN 2010jl, which was inferred to have an unabsorbed luminosity of \( L_X \sim 7 \times 10^{42} \, \text{erg s}^{-1} \), most likely from the forward shock front at \( \sim 10^{17} \, \text{cm} \) (Chandra et al. 2012a). However, the actual observed luminosity was initially only 20 per cent of the unabsorbed luminosity, at least during an early epoch, as the column density was immense: \( \sim 10^{34} \, \text{cm}^{-2} \). Several other SNe have been observed to have X-ray luminosities of a few \( 10^{41} \, \text{erg s}^{-1} \) more than a year post-explosion, for example SN 2008iy (Miller et al. 2010), SN 1995N (Fox et al. 2000) and SN 1988Z (Aretxaga et al. 1999); in particular, SN 1988Z may have radiated \( \sim 50 \) per cent of its total explosion energy in X-rays in just 10 years, confirming that a dense CSM can convert a large fraction of the kinetic energy of an SN into X-ray radiation. Indeed, the X-ray light curves of all observed X-ray SNe found in the literature had peak luminosities ranging from \( 10^{37} \) to almost \( 10^{43} \, \text{erg s}^{-1} \) (Dwarkadas & Gruszko 2012), which may be puzzling given our calculation that \( 10^{34} - 10^{44} \, \text{erg s}^{-1} \) X-ray luminosities with durations of several months are theoretically allowed even with modest explosion energies of \( 10^{51} \, \text{erg} \), albeit contingent on the existence of a CSM shell and some fine tuning of the shell parameters. But almost all of these X-ray SNe were observed below 10 keV, whereas most luminous X-ray events proposed here are driven by fast forward shocks that can reach temperatures of \( T \sim 10^9 \, \text{K} \), so before the shock escapes the CSM shell, many unabsorbed X-ray photons from the early emission will have energies \( > 10 \, \text{keV} \).

Therefore, the newly launched NuSTAR space telescope, which can observe up to 80 keV, may be better suited for capturing superluminous X-ray SNe during early CSM interactions compared with previous satellites. Although the Burst Alert Telescope on Swift can also observe up to 150 keV, its poor sensitivity allows it to see \( 10^{46} \, \text{erg s}^{-1} \) objects only out to \( \sim 10 \, \text{Mpc} \).

Moreover, the event rate of our proposed superluminous X-ray SNe should be comparable to the rate of optically superluminous SNe powered by strong shocks from ejecta-CSM interactions, i.e. \( \lesssim 10^{-8} \, \text{Mpc}^{-3} \, \text{yr}^{-1} \); given their scarcity, we were not discouraged by the lack of reported detections in the literature. However, after we submitted our paper and posted it on arXiv, Levan et al. (2013) revealed analysis of X-ray observations of SCP 06F6 that showed that it is likely the brightest X-ray SN ever observed, with \( L_X \sim 10^{45} \, \text{erg s}^{-1} \). It is plausible that the superluminous X-ray emission from SCP 06F6 may be powered by converting a significant fraction of \( \sim 10^{52} \, \text{erg} \) of explosion energy via the interaction of SN ejecta with a dense CSM, consistent with the fact that SCP 06F6 was also an optically superluminous SN.

If the SN ejecta collides with a dense CSM shell, the shell acts as a wall, resulting in a high reverse shock velocity of \( \approx v_{\text{SN}} - v_{\text{s}} \). When the energy initially transmitted into the shell is small, the solutions for the reverse shock have a self-similar nature, and were first solved by Chevalier & Liang (1989). As the CSM shells in our superluminous scenarios tend to be much denser than the cavity within (even if the SN ejecta mass is included and averaged over the cavity), it is likely that the luminosity of the forward shock running in the CSM shell will dominate the reverse shock retreating into the cavity; furthermore, the reverse shock emission is subject to heavy absorption from the cold, dense shell that condenses between the forward and reverse shocks.

Optical and X-ray emission, interpreted as generated from interactions between SN ejecta and CSM (or between two ejected shells), have already been used to provide indirect evidence for the explosive ejection of massive CSM shells a few years prior to the supernova, e.g. SN 1994W (Chugai et al. 2004; Dessart et al. 2009). Several observed SNe have a CSM density that seemed to increase with distance from the progenitor: SN 2008iy (Miller et al. 2010), SN 1990cr (Bauer et al. 2008), SN 2001em (Chugai & Chevalier 2006; Schinzel et al. 2009) and SN 2011ja (Chakrabarti et al. 2013), suggesting that at least at certain radii, the CSM may be better modelled as a CSM shell rather than a smooth \( r^{-2} \) wind (Fox et al. 2013). Also, some of the ultraluminous X-ray sources with luminosities up to \( \sim 10^{44} \, \text{erg s}^{-1} \), especially the ones with a thermal spectrum and slow variability, may be due to SN interacting with massive circumstellar shells (Swartz et al. 2004).

Aside from converting the kinetic energy of expanding ejecta into radiation upon collision with a massive CSM shell, there is another main mechanism invoked to power a superluminous SN. In this mechanism, the SN explosion launches a shock wave from the centre of the star, with the shock heating the material it crosses as the shock travels outwards, until the shock escapes at a radius where the material is no longer optically thick to radiation. More specifically, this shock breakout occurs when the photon diffusion time-scale becomes shorter than the dynamical time-scale of the shock, corresponding to an optical depth of \( \tau \approx c/v_s \) (Weaver 1976); for superluminous SN, this edge is at least an order of magnitude greater than the edge of the gravitationally bound progenitor star. Then, the thermal energy deposited by the shock is gradually emitted as photons diffuse out, analogous to regular Type IIP SNe (Gal-Yam 2012).

Many ways have been proposed to explain the large effective radii required for superluminous light curves powered via shock breakout, including massive and optically thick stellar winds (Ofek et al. 2010; Chevalier & Irwin 2011; Moriya & Tominaga 2012; Moriya et al. 2013), or massive and optically thick shells ejected in prior eruptions (Smith & McCray 2007; Miller et al. 2009) – assuming that the CSM is optically thick all the way to the CSM shell. A shock breakout in such environments could also produce X-ray emission (Balberg & Loeb 2011; Katz, Sapir & Waxman 2011; Chevalier & Irwin 2011; Svirski, Nakar & Sari 2012), and searches for such events have been conducted (Ofek et al. 2013b). The unabsorbed X-ray emission from these shock breakouts can also reach incredible luminosities \( \sim 10^{44} \, \text{erg s}^{-1} \); however, the luminosity after shock breakout tends to decline quickly with time, whereas the X-ray emission from optically thin CSM shell interactions can increase for an extended period of time as the shock runs through and superheats more of the shell. The collision of SN ejecta with massive CSM shells can also emit much larger total energies in X-rays. Furthermore, the delay between the optical SN and the X-ray emission is much shorter for shock breakouts.

A non-thermal power-law population of relativistic electrons may be accelerated by the shock. These could inverse-Compton scatter soft photons and also emit in optical and UV up to X-rays and high-energy \( \gamma \)-rays. The X-rays from this inverse-Compton component is likely negligible compared to the luminous X-ray emission from the forward shock running through a dense CSM shell considered in this paper, as the former scales with density while the latter scales with density squared; Chevalier & Fransson (2006) found that during the plateau phase of a Type IIP SN, when the optical flux of the SN is still \( \sim 10^{42} \, \text{erg s}^{-1} \), the inverse-Compton X-ray
emission is less than $10^{37}$ erg s$^{-1}$, and will further decrease with time as the soft photon flux diminishes. We should also mention the possibility that the collision of SN ejecta with massive CSM shells can serve as potential cosmic ray accelerators (Murase et al. 2011).

ACKNOWLEDGEMENTS

We thank Sayan Chakraborti, Manos Chatzopoulos, Raffaella Margutti, Takashi Moriya, John Raymond and Randall Smith for useful discussions. TP was supported in part by NSF grant AST-0907890 and the National Science Foundation via a graduate research fellowship. This work was supported in part by NSF grant NNX08AL43G and NASA grants NNX08AL43G and NNA09DB30A.

REFERENCES

Aretxaga I., Benetti S., Terlevich R. J., Fabian A. C., Cappellaro E., Turatto M., della Valle M., 1999, MNRAS, 309, 343
Balberg S., Loeb A., 2011, MNRAS, 414, 1715
Bauer F. E., Dwarkadas V. V., Brandt W. N., Immler S., Smartt S., Bartel N., Bietenholz M. F., 2008, ApJ, 688, 1210
Blondin J. M., Lundqvist P., 1993, ApJ, 405, 337
Burrows D. N. et al., 2000, ApJ, 543, L149
Chakraborti S. et al., 2013, preprint (arXiv:e-prints)
Chandra P., Chevalier R. A., Irwin C. M., Chugai N., Fransson C., Soderberg A. M., 2012a, ApJ, 750, L2
Chandra P., Chevalier R. A., Chugai N., Fransson C., Irwin C. M., Soderberg A. M., Chakraborti S., Immler S., 2012b, ApJ, 755, 110
Chatzopoulos E., Wheeler J. C., 2012, ApJ, 760, 154
Chevalier R. A., 1982a, ApJ, 258, 790
Chevalier R. A., 1982b, ApJ, 259, 302
Chevalier R. A., Fransson C., 1994, ApJ, 420, 268
Chevalier R. A., Fransson C., 2003, in Weiler K., ed., Lecture Notes in Physics, Vol. 598, Supernovae and Gamma-Ray Bursters. Springer-Verlag, Berlin, p. 171
Chevalier R. A., Fransson C., 2006, ApJ, 651, 381
Chevalier R. A., Irwin C. M., 2011, ApJ, 729, L6
Chevalier R. A., Irwin C. M., 2012, ApJ, 747, L17
Chevalier R. A., Liang E. P., 1989, ApJ, 344, 332
Chugai N. N., 1993, ApJ, 414, L101
Chugai N. N., Chevalier R. A., 2006, ApJ, 641, 1051
Chugai N. N. et al., 2004, MNRAS, 352, 1213
Davidson K., Humphreys R. M., 2012, Astrophysics and Space Science Library, Vol. 384, Eta Carinae and the Supernova Impostors. Springer, New York, p. 267
Dessart L., Hillier D. J., Gezari S., Basa S., Matheson T., 2009, MNRAS, 394, 21
Dwarkadas V. V., 2005, ApJ, 630, 892
Dwarkadas V. V., Grusko J., 2012, MNRAS, 419, 1515
Foley R. J., Smith N., Ganeshalingam M., Li W., Chornock R., Filippenko A. V., 2007, ApJ, 657, L105
Fox D. W. et al., 2000, MNRAS, 319, 1154
Fox O. D., Filippenko A. V., Skrutskie M. F., Silverman J. M., Ganeshalingam M., Cenko S. B., Clubb K. I., 2013, preprint (arXiv:e-prints)
Franco J., Melnick J., Terlevich R., Tenorio-Tagle G., Rozyczka M., 1993, in Franco J., Ferrini F., Tenorio-Tagle G., eds, Star Formation, Galaxies and the Interstellar Medium. Cambridge Univ. Press, Cambridge, p. 149
Gal-Yam A., 2012, Sci, 337, 927
Gal-Yam A., Leonard D. C., 2009, Nat, 458, 865
Gal-Yam A. et al., 2007, ApJ, 656, 372
Gal-Yam A. et al., 2009, Nat, 462, 624
Ginzburg S., Balberg S., 2012, ApJ, 757, 178
Heger A., Woosley S. E., 2002, ApJ, 567, 532
Katz B., Sapir N., Waxman E., 2011, preprint (arXiv:e-prints)
Kiewe M. et al., 2012, ApJ, 744, 10
Levan A. J., Read A. M., Metzger B. D., Wheatley P. J., Tanvir N. R., 2013, preprint (arXiv:e-prints)
Mauerhan J. C. et al., 2013, MNRAS, 430, 1801
Miller A. A. et al., 2009, ApJ, 690, 1303
Miller A. A. et al., 2010, MNRAS, 404, 305
Moriya T. J., Tominaga N., 2012, ApJ, 747, 118
Moriya T. J., Binnikov S. I., Tominaga N., Yoshida N., Tanaka M., Maeda K., Nomoto K., 2013, MNRAS, 428, 1020
Murase K., Thompson T. A., Lacki B. C., Beacom J. F., 2011, Phys. Rev. D, 84, 043003
Ofek E. O. et al., 2010, ApJ, 724, 1396
Ofek E. O. et al., 2013a, Nat, 494, 65
Ofek E. O. et al., 2013b, ApJ, 763, 42
Owocki S. P., Gayley K. G., Shaviv N. J., 2004, ApJ, 616, 525
Patnaude D. J., Ellisin D. C., Slane P., 2009, ApJ, 696, 1956
Quataert E., Shiode J., 2012, MNRAS, 423, L92
Raymond J. C., Cox D. P., Smith B. W., 1976, ApJ, 204, 290
Rest A. et al., 2011, ApJ, 729, 88
Schnizel F. K., Taylor G. B., Stockdale C. J., Granot J., Ramirez-Ruiz E., 2009, ApJ, 691, 1380
Sgro A. G., 1975, ApJ, 197, 621
Shaviv N. J., 2000, ApJ, 532, L137
Smith N., McCray R., 2007, ApJ, 671, L17
Smith N., Chornock R., Li W., Ganeshalingam M., Silverman J. M., Foley R. J., Filippenko A. V., Barth A. J., 2008, ApJ, 686, 467
Smith N., Li W., Silverman J. M., Ganeshalingam M., Filippenko A. V., 2011, MNRAS, 415, 773
Spitzer L., 1962, Physics of Fully Ionized Gases. Dover Press, New York
Svirski G., Balberg S., 2012, ApJ, 759, 108
Swartz D. A., Ghosh K. K., Tennant A. F., Wu K., 2004, ApJS, 154, 519
Tarter C. B., Tucker W. H., Salpeter E. E., 1969, ApJ, 156, 943
Terlevich R., Tenorio-Tagle G., Franco J., Melnick J., 1992, MNRAS, 255, 713
Truelove J. K., McKee C. F., 1999, ApJS, 120, 299
Weaver T. A., 1976, ApJS, 32, 233
Woosley S. E., Blinnikov S., Heger A., 2007, Nat, 450, 390

This paper has been typeset from a TeX/ΛTEX file prepared by the author.