Rebound Shock Breakouts of Exploding Massive Stars: A MHD Void Model

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Abstract. With a self-similar magnetohydrodynamic (MHD) model of an exploding progenitor star and an outgoing rebound shock and with the thermal bremsstrahlung as the major radiation mechanism in X-ray bands, we reproduce the early X-ray light curve observed for the recent event of XRO 080109/SN 2008D association. The X-ray light curve consists of a fast rise, as the shock travels into the "visible layer" in the stellar envelope, and a subsequent power-law decay, as the plasma cools in a self-similar evolution. The observed spectral softening is naturally expected in our rebound MHD shock scenario. We propose to attribute the "non-thermal spectrum" observed to be a superposition of different thermal spectra produced at different layers of the stellar envelope.

Keywords: Gamma-ray bursts (GRBs) — MHD — shock waves — star: winds, outflows — supernovae — X-rays
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INTRODUCTION

SN 2008D, the best type Ibc supernova detected so far, is preceded by a X-Ray Outburst (XRO) captured by SWIFT satellite on 2008 January 9, and this XRO is interpreted as a shock breakout of a Wolf-Rayet (WR) progenitor with a radius of $\sim 10^{11}$ cm [1]. The isotropic X-ray energy is estimated to be $\sim 2\times 10^{46}$ erg, and there seems no collimation detected so the event is not regarded as a GRB. This XRO showed a rapid rise, peaked at ~ 63 s, and a decay modelled to be exponential with an e-folding time of ~ 129 s [1]. The follow-up optical and ultraviolet observations indicate a total supernova kinetic energy of $\sim 2-4\times 10^{51}$ erg and a mass of SN ejecta to be $\sim 3-5$ $M_\odot$ [1]. Some authors estimate from a detailed spectral analysis that SN 2008D, originally a ~ 30 $M_\odot$ star, has a spherical symmetric explosion energy of $\sim 6\times 10^{51}$ erg and an ejected mass ~ 7 $M_\odot$ [2]. The evolution of optical spectra of XRO-SN 2008D resembles that of XRO-SN 2006aj, whose progenitor is also believed to be a WR star [3].

The production of γ-rays and X-rays by shock breakouts has been proposed earlier [4, 5]. This XRO and the associated SN present an unprecedented case to be investigated in details, especially on interpretations for the rise and decay times of the X-ray light curve. The claim of an exponential decay may be premature given a fairly large scatter, and it may have concealed valuable physical clues offered by this XRO. During the XRO, the observed spectroscopic softening still lacks a convincing explanation. Here, we advance a self-similar MHD rebound shock model in an attempt to reproduce the observed X-ray light curve. The next section contains an overall description of the self-similar MHD model and the procedure of analysis; in the third section, we compare our model results with data; and conclusions are summed up in the last section.

A SELF-SIMILAR MHD VOID SHOCK MODEL

For a polytropic magnetofluid in quasi-spherical symmetry under the self-gravity, the governing magnetohydrodynamic (MHD) equations include mass conservation, momentum conservation (Euler equation), magnetic induction equation, and an equation of specific entropy conservations along streamlines to approximate energetic processes. For this more general polytropic equation of state, we regard the polytropic index γ as a parameter [11].

These coupled nonlinear MHD partial differential equations (PDEs) can be reduced to nonlinear ordinary differential equations (ODEs) by introducing a self-similar transformation $r = k^{1/2}xt^n$, where r is the radius, t is the time and k is a scale parameter relevant to the local sound speed, rendering the independent self-similar variable x dimensionless. The corresponding transformation of the dependent MHD variables can be found in refs. [11, 16]. The exponent n is a key parameter that determines the dynamic behaviour of a polytropic fluid. For $n+\gamma = 2$, the formulation reduces to that of a conventional polytropic gas in which the specific entropy remains constant everywhere [20, 21, 6, 7, 10]. The special case of $n = 1$ and $\gamma = 1$ corresponds to the isothermal case [13, 14]. Such self-similar evolutions represent an important subclass of all possible evolutions. We also introduce a dimensionless magnetic parameter to represent the strength of a magnetic field $h \equiv < B_t^2 > /(16\pi^2 G\rho^2 r^2)$, where $< B_t^2 >$ is the ensemble average of a random transverse magnetic field squared, G is the gravity constant and ρ is the mass density. Meanwhile, MHD shocks are necessary to connect different branches of self-similar solutions. The conservation laws impose constraints on physical variables across a MHD shock front. We can then derive downstream physical quantities (density, velocity, pressure and temperature) from the upstream physical quantities or vice versa. Self-similar solutions produce radial profiles of density, radial velocity, pressure and temperature at any time of evolution, and the detailed procedure of analysis can be found in the reference of Wang & Lou [11]. It is also sensible to invoke the plasma cooling function and obtain radiation diagnostics from a magnetofluid of high temperatures $\sim 10^7 - 10^8$K [18].

Recently, we obtained a new class of self-similar "void" solutions within a certain radius r^* referred to as the void boundary. In general, such a void solution describes an expanding fluid envelope with a central cavity and possibly associated with an outgoing shock [12]. The self-similar evolution implies that the central void expands as a power-law in time $r^* \propto t^n$. We study detailed behaviours of void solutions under different parameters in a general polytropic MHD framework [15, 16]. Here, we propose to utilize such void shock solutions to model the explosion of a massive progenitor star in the process of a rebound MHD shock breakout. The Bondi-Parker radius of a remnant compact object if any left in the center is defined as

$$r_{\rm BP} = \frac{GM_*}{2a^2} \ , \tag{1}$$

where M_* is the mass of the central object and a is the sound speed at the inner void edge of the surrounding gas. Far beyond this radius $r_{\rm BP}$, the gravity of the central object becomes negligible compared to the thermal pressure. For supernovae, M_* would be of the order of $M_\odot$ [2]. At ~ 1 s after the core bounce, the temperature of the stellar envelope is of the order of 10^8 K, and the sound speed $a^2 \sim 10^{17}$ cm^2 s^{-2}, and then $r_{\rm BP} \sim 10^8$ cm. Meanwhile, the void radius r^* expands to larger than 10^8 cm [17]. Furthermore, the Bondi-Parker radius expands slower than the void boundary does [16]. Therefore, the cavity assumption may be justifiable.

MHD MODEL AND X-RAY LIGHT CURVE

The self-similar MHD void shock model of a WR stellar envelope in explosion associated with a shock breakout and the corresponding X-ray light curve are shown in Figure 1.

Following observational inferences [1] for the progenitor radius, we cut off our model at this "outer boundary" ($r_{\rm out} \sim 10^{11}$ cm). This approximation is reasonable, as the radial density profile of the star drops rapidly at the stellar surface. We do not consider dynamical effects and the X-ray contributions of the gas outside $r_{\rm out}$. Our MHD model gives an enclosed mass at $\sim 10^{11}$ cm to be 3.8 $M_\odot$, comparable to the estimated mass of ejecta ($\sim 3-5\ M_\odot$). The gas kinetic energy is $\sim 3 \times 10^{51}$ erg, also in the observed range. The gravitational binding energy given by our model is $\sim 10^{50}$ erg, much less than the kinetic energy corresponding to an exploding stellar envelope during a MHD rebound shock breakout.

In Figure 1, we see features of a rebound MHD shock surrounding a central void in self-similar expansion. From the upstream to downstream sides across the shock, the density, pressure and temperature increases suddenly. The radial velocity also increases, but the velocity in the shock comoving reference framework decreases as expected from the upstream to downstream sides. Note that the temperature is $\sim 10^8$ K and it drops to $\sim 10^7$ K in the process of the evolution under consideration, corresponding to the energy range of X-ray photons detected. Typically the part of gas near the downstream shock front, where the density and temperature are the highest, is most efficient in producing X-ray emissions. We suggest that X-ray emissions observed are from the thermal bremsstrahlung radiation mainly produced around the downstream side of a rebound shock.

We compute the X-ray light curve using the plasma cooling rate result of reference [18, see also Lou & Zhai 2008 in preparation for X-ray diagnostics of isothermal voids in self-similar expansion], in which both the free-free and free-bound emissions are taken into account. The optical depth in the stellar envelope is unknown, so we treat it as another parameter to search for the best fit of X-ray light curve. Here we introduce an "inner boundary" $r_{\rm in}$, and presume that only X-ray emissions in the layer between $r_{\rm in}$ and $r_{\rm out}$ can be observed and should be integrated. The thickness of such "radiative layer" noted as s is another parameter to adjust.

Our scenario is as follows. The MHD rebound shock front expands outward obeying a power law in time t since the core collapse, and the shock strength weakens with increasing t. Before the shock front reaches $r_{\rm in}$, the density and temperature are low in the radiative layer and cannot produce detectable X-ray emissions. Once the shock front reaches

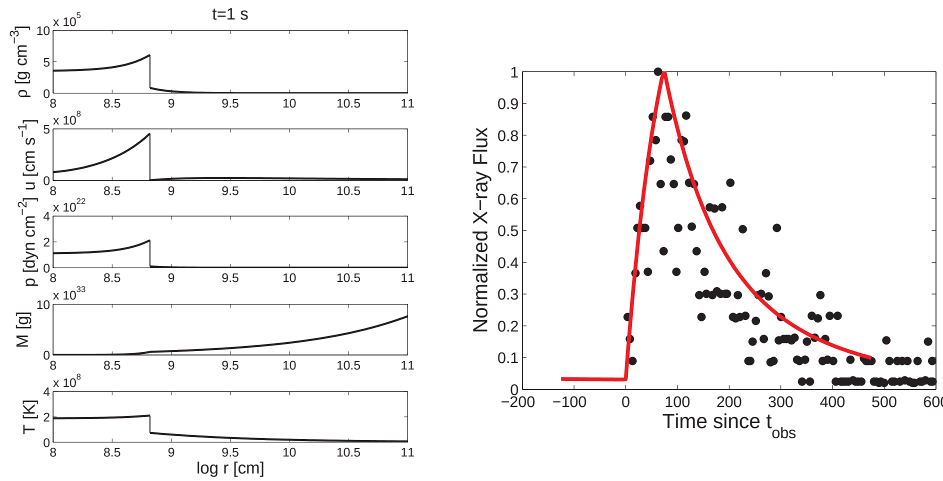

FIGURE 1. Our MHD void shock model for a shock breakout in a progenitor of SN 2008D (left) and the resulting X-ray light curve (right). On the left from top to bottom, the panels show the radial profiles of density, radial velocity, pressure, enclosed mass and temperature of the stellar envelope within radial range 10^8 cm (void boundary) and $\sim 10^{11}$ cm (outer boundary) at 1 s after the core collapse and rebounce. The model is obtained with the self-similar parameters as $n = 0.8$, $\gamma = 1.2$ (conventional polytropic) and $h = 0$ (non-magnetized fluid). On the right, we compare the X-ray light curve calculated from our MHD void shock model (red curve) and data from the X-Ray Telescope (XRT) on board the SWIFT satellite [1] (solid circles with error bars suppressed). X-ray fluxes are normalized to the peak flux. The X-ray light curve is shown as a function of time since the XRT trigger, noted as $t_{\rm obs}$. The core collapse happened ~ 552 s before the trigger. The X-ray light curve is calculated with the radiation layer thickness to be 9×10^9 cm. The calculated X-ray light curve is in a shape of fast-rise-and-decay. The rise time is ~ 62 s, and the decay obeys a power law to the time since core collapse with the index to be -4.3. The equivalent e-folding is 128 s (i.e., the timescale when the emission intensity drops to $\sim 37\%$ of the peak value).

$r_{\rm in}$ and runs into the radiative layer, more and more downstream part enters the radiative layer, and X-ray emissions increase rapidly. The X-ray emission reaches its maximum when the shock front reaches $r_{\rm out}$ (shock breakout) and the entire radiative layer is occupied by the downstream part. Thereafter, the density and temperature inside the radiative layer decrease self-similarly, and the X-ray emission decreases obeying a power law. The radiative layer thickness s and the shock speed determine the rise time and the power law index of the subsequent decay. The average temperature of the radiative layer decreases self-similarly in the shock breakout process, naturally leading to the spectral softening as observed.

SUMMARY AND CONCLUSIONS

With a self-similar MHD void shock model and the thermal bremsstrahlung as the main radiation loss, we obtain a fairly good fit to the X-ray light curve observed and confirm that XRO 080109 is most likely a shock breakout event. We identify that the decay in the X-ray light curve follows a power law (instead of an exponential law) in time since the core collapse and rebounce, which occurred ~ 552 s before the observation of X-ray emissions. Meanwhile, the spectral softening is expected qualitatively. In this work, we use the most simplified radiation transfer presumption that the radiation produced in the ‘visible layer’ can be totally observed. Actually, the optical depth varies with radius and should be treated in a more elaborate manner. Additionally, we presume that the boundaries of the “visible layer" r_{in} and r_{out} do not vary with time. Despite all these idealizations, our self-similar dynamic approach appears to be suitable to couple with the radiation process and to model X-ray outbursts in supernova as observed.

Regarding the X-ray spectra observed, they cannot be fitted with a simple blackbody profile, and a nonthermal power law profile was suggested [1]. Several mechanisms have been proposed to explain such X-ray spectra, for example the bulk comptonization by scatterings of the photons between the ejecta and a dense circumstellar medium [1], or diluted thermal spectra which require the thermalization occurs at a considerable depth in the supernova [19]. We propose that the power-law profile might be a natural result of multi-colour superposition of blackbody spectra. Based on our scenario outlined here, X-ray emissions come from different layers within the radiative layer around the stellar surface, and the radiative layer has different temperatures at different depth. As a result, the observed X-ray spectra are the superposition of thermal blackbody components with different temperatures. We suggest that this might resolve issues of spectral profile and evolution.

During breakouts of rebound shocks and in the presence of MHD shock accelerated relativistic electrons usually presumed with a power-law energy spectrum within a certain electron energy range, we could also compute synchrotron emissions associated with such kind of SN shock breakouts. Among others, it is then possible to follow the evolution of magnetic field strength associated with SN explosions [8, 7] and estimate the effectiveness of accelerating relativistic particles (i.e., high-energy cosmic rays [9]). There is the freedom of choosing a few parameters to fit the data at a certain epoch. It is then possible to test the hypothesis of a self-similar shock evolution by further observations. In a more general perspective and on the basis of our dynamic models for rebound MHD shocks, we hope to further develop radiative diagnostics for shock breakouts of supernovae and thus for SN related GRBs.

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