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The Progenitor of SN2008D was a Wolf-Rayet Star Based on Its Shock Breakout Lightcurve

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ABSTRACT

We show that the radius of a supernova progenitor, $R_\star$, can be tightly constrained based on a simple analysis of its shock breakout lightcurve. The peak luminosity and the characteristic decline time in the breakout lightcurve already yield a robust upper limit on this radius. Further assumptions about the progenitor's mass, surface density profile and the energy of the explosion can be used to determine the actual value of the radius. We demonstrate this method in the case of XRO080109/SN2008 for which $R_\star < 6 \times 10^{11}$cm, suggesting that the progenitor was a Wolf-Rayet star. Assuming a surface density profile $\rho(r) \propto (1 - r/R_\star)^3$, we find $R_\star \approx 2 \times 10^{11}$cm, with a weak dependence on the explosion energy and progenitor mass. This estimate is roughly consistent with the radius estimates based on the UV/Optical data.

Key words: Supernovae, X-ray, SN2008D

1 INTRODUCTION

...the shock propagates towards the edge of the star at $R_\star$. Its position and velocity are r_s and v_s, respectively, and we will use the dimensionless quantity $x_s = (1 - r_s/R_\star)$... Denoting the radial position of the breakout by x_{BO} and r_{BO}....

$$t_{\rm dyn} \approx t_{\rm diff} \tag{1}$$

where $t_{\rm dyn}$ is the dynamical time and $t_{\rm diff}$ is the diffusion time scale. Both can be estimated at the shock radius, by

$$t_{\rm dyn} = \frac{R_\star x_{BO}}{v_s(x_{BO})} \tag{2}$$

and

$$t_{\rm diff} = \frac{(R_\star x_{BO})^2}{c/3\kappa\rho(x_{BO})} \tag{3}$$

At the shock front, energy is converted into into internal energy over a dynamical timescale. Hence, equation (1) simply states that at the breakout shell, energy is radiated away at the same rate that it is added. The observed X-ray luminosity, L_X, should be comparable to the rate at which kinetic energy is advected in the rest frame of the shock,

$$\dot{E}_{\rm kin}(x_{BO}) = 4\pi r_{BO}^2 \frac{1}{2}\rho(x_{BO}) v_{BO}^3 \tag{4}$$

where we assume a non-relativistic shock velocity - an assumption that will be checked for consistency below. For a radiation dominated shock the internal energy in the radiation is 6/7 of the incoming kinetic energy, with the remaining 1/7 going to kinetic energy of the post shock material. After setting $L_X = 6\dot{E}_{\rm kin}/7$ and substituting $v_s(r_s)$ and $\rho(r_s)$ from equations (2) and (3) we find that

$$L_X \approx 2\pi r_{BO}^2 \frac{c t_{\rm diff}}{(R_\star x_{BO})^2 \kappa} \left[\frac{(R_\star x_{BO})}{t_{\rm diff}}\right]^3 \tag{5}$$

or

$$R_\star \approx 9.63 \times 10^{10}\ {\rm cm} (1 - x_{BO,5})^{2/3} x_{BO,5}^{1/3} \kappa_{0.34}^{1/3} (L_{X,43} t_{\rm diff,2}^2)^{1/3} \tag{6}$$

where $\kappa_{0.34} = (\kappa/0.34\ {\rm cm^2 g^{-1}})$, $L_{X,43} = (L_x/10^{43} {\rm erg\ s^{-1}})$ and $t_{\rm diff,2} = (t_{\rm diff}/10^2{\rm s})$. Even in the absence of additional information, this result yields a rather stringent constraint. While scaling the value of x_{BO} is justified in hindsight (see below), the function $(1 - x_{BO})^2 x_{BO}$ has an obvious maximum at $x_{BO} = 1/3$, for which the prefactor in Eq. (6) is larger by only a factor of 3. Correspondingly, measurement of L_X and $t_{\rm diff}$ alone can place an upper limit on the radius of the progenitor, while making no additional assumptions about its density profile, apart for keeping the shock non-relativistic.

In the case of SN2008D $L_{X,43} = 6.1$ and $t_{\rm diff,2} = 1.2$, leading to a maximum radius of $6.17 \times 10^{11} \kappa_{0.34}^{1/3}$cm, suggesting already that the progenitor was a Wolf-Rayet star.

In order to place a tighter constraint on the progenitor radius we must make further assumptions about the structure of the star and the energy of the explosion. The breakout is expected to occur when the shock width becomes comparable to the distance from the breakout shell to edge of the star, or that the optical depth from the breakout shell is $\sim c/v_s$. For an envelope density profile of $\rho(r) = \rho_\star x^n$ the

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optical depth from a shell of given x to the edge of the star is

$$\tau(x) = \frac{R_\star \rho_* \kappa x^{(n+1)}}{n+1} \tag{7}$$

while the shock velocity increases with decreasing x as

$$v_s(x) = A_v \left(\frac{4\pi}{3f\rho}\right)^{\beta} \left(\frac{E}{M}\right)^{1/2} x^{-n\beta} \tag{8}$$

where A_v, f_ρ and β are constants which depend on the properties of the star. Specifically, $f_\rho \equiv \rho_\star/\bar{\rho}$, where $\bar{\rho}$ is the average density of the star. Solving equations (7) and (8) yields yet another relation between $R_\star$ and x_{BO}.

$$R_\star = (EM)^{1/4} \left(\frac{3f_\rho}{4\pi}\right)^{(1-\beta)/2} \left(\frac{A_v \kappa}{c}\right)^{1/2} x_{BO}^{(n+1-\beta n)/2} \tag{9}$$

Setting $n = 3$ appropriate for a Wolf-Rayet star, $\beta = 0.19$ $A_v = 0.8$ and $f_\rho = 1$, we find

$$R_\star = 1.78 \times 10^{11} (E_{51} M_{10} \kappa_{0.34}^2)^{1/4} x_{BO,5}^{1.715} \tag{10}$$

Where $E_{51} = (E/10^{51})$ergs and $M_{10} = (M/10M_\odot)$.

Equation (10) along with eq. (6) solve x_{BO} and $R_\star$ for assumed values of E_{51} and M_{10}. The result is that x_{BO} has a relatively weak dependence on these values, $x_{BO} \propto (E_{51}M_{10})^{-0.18})$, and $R_\star \propto (E_{51}M_{10})^{-0.06}$. Hence the estimate of $R_\star$ is almost independent of the unknown parameters of the explosion.

In the case of SN2008D we now arrive at a final result

$$x_{BO,5} = 1.083(E_{51}M_{10})^{-0.18}; R_\star = 2.1 \times 10^{11} cm \tag{11}$$

Things to add:

*Begin by explaining why the maximum luminosity is $4\pi r^2 \rho(r) v_s^3$ - this is because breakout means that the shock loses as much energy as it creates - further out the shock weakens considerably and the energy generation rate decreases.

*Mention that $R_\star/c$ is unimportant in this case.

*Show that the velocity is indeed non-relativistic: That is the case unless the ejecta has a mass of about $M = 1M_\odot$ (rather than $10M_\odot$) or if the energy is several times 10^{51} ergs.

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