The X-Ray Transient 080109 in NGC 2770: an X-Ray Flash Associated with a Normal Core-Collapse Supernova

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ABSTRACT
Although it is generally thought that long-duration gamma-ray bursts (LGRBs) are associated with core-collapse supernovae (SNe), so far only four pairs of GRBs and SNe with firmly established connection have been found. All the four GRB-SNe are among a special class of Type Ic—called the broad-lined SNe indicative of a large explosion energy, suggesting that only a small fraction of SNe Ibc have GRBs associated with them. This scheme has been refreshed by the discovery of a bright X-ray transient in NGC 2770 on 9 January 2008, which was followed by a rather normal Type Ib SN 2008D. In this paper, I argue that the transient 080109 is an X-ray flash (XRF, the soft version of a GRB) because of the following evidences: (1) The transient cannot be interpreted as a SN shock breakout event; (2) The GRB X-ray flare interpretation is not supported by the high-energy observation. Then I show that XRF 080109 satisfies the well-known relation between the isotropic-equivalent energy and the peak spectral energy for LGRBs, which highly strengthens the XRF interpretation. Finally, I point out that, the peak spectral energy of XRF 080109 and the maximum bolometric luminosity of SN 2008D agree with the $E_{\gamma,\text{peak}}-L_{\text{SN,max}}$ relationship of Li (2006), strengthening the validity of the relationship. I speculate that events like XRF 080109 may occur at a rate comparable to SNe Ibc, and a soft X-ray telescope devoted to surveying for nearby X-ray flares will be very fruitful in discovering them.

Key words: gamma-rays: bursts – supernovae: general – supernovae: individual: SN 2008D.

1 INTRODUCTION

On 9 January 2008, a luminous X-ray transient was discovered during follow-up observations of SN 2007uy in NGC 2770 with the X-Ray Telescope (XRT) onboard Swift (Berger & Soderberg 2008; Kong & Maccarone 2008; Soderberg et al. 2008). The transient event, which lasted about 600 s before decaying to the background level, was later confirmed to occur in the same galaxy of SN 2007uy (at redshift $z = 0.00649^1$) by the observation of an optical counterpart and a supernova (SN), named SN 2008D, accompanying the transient (Deng & Zhu 2008; Imler et al. 2008; Malesani et al. 2008a,b; Valenti et al. 2008a,b; Blondin, Matheson & Modjaz 2008; Thorstensen 2008; Li et al. 2008).

The SN underwent a transition from Type Ic to Type Ib (Modjaz et al. 2008; Valenti et al. 2008b), similar to the case of SN 2005bf (Wang & Baade 2005; Modjaz et al. 2005; Anupama et al. 2005; Tominaga et al. 2005). In addition, the spectra of the SN exhibited rather broad features at early epochs, although not as broad as the earliest spectra of the so-called ‘hypernovae’ associated with gamma-ray bursts (GRBs) such as SN 1998bw and SN 2006aj (Malesani et al. 2008a; Valenti et al. 2008a; Blondin et al. 2008). Despite these unusual characteristics compared to typical SNe Ibc like 1994I, I call SN 2008D a ‘normal’ SN as opposed to broad-lined GRB-SNe like 1998bw as suggested by other people (Malesani et al. 2008b; Valenti et al. 2008b; Soderberg et al. 2008).

The nature of the transient 080109 is debatable. Several possibilities for the nature have been proposed: (a) SN shock breakout (Burrows et al. 2008; Soderberg et al. 2008); (b) X-ray flash (XRF, the soft version of a GRB) (Berger & Soderberg 2008, Xu, Zou & Fan 2008); (c) X-ray flare of a GRB (Burrows et al. 2008).

The total energy emitted by the transient is $\approx 1.3 \times 10^{46}$ erg in the XRT energy range 0.3–10 keV (Section 2). Although this energy is within the range predicted for shock breakout in SNe Ibc (L $\approx 2007\alpha$) and the transient occurred ahead of SN 2008D, the spectrum of the transient is not a blackbody, and the event duration is too long for a typical shock breakout event in a Type Ib SN (L $\approx 2007\alpha$). Hence,
the shock breakout interpretation does not seem to be correct (stronger arguments are given in Section 3; see also Xu et al. 2008).

The transient 080109 was in the field of view of the Burst Alert Telescope (BAT) onboard 
Swift beginning half an hour before and continuing throughout the outburst. However, no gamma-ray counterpart was detected (Burrows et al. 2008). Hence, it is also unlikely that the transient was an X-ray flare of a GRB.

Then, the only remaining interpretation on the nature of the transient 080109 is that it is an XRF. In this paper I will show that, despite its extremely soft spectrum compared to that of a normal XRF or a GRB, the transient 080109 is naturally interpreted as an XRF in the context of the GRB-SN connection.

An important discovery in the observation of GRBs has been the connection between long-duration GRBs (with a duration > 2 s) and SNe (Piran 2004; Della Valle 2006; Woosley & Bloom 2006; Nomoto et al. 2008; and references therein). So far, four pairs of spectroscopically confirmed GRBs/SNe have been discovered: GRB 980425/ SN 1998bw (Galama et al. 1998), GRB 030329/SN 2003dh (Stanek et al. 2003; Hirst et al. 2003), GRB 031203/SN 2003lw (Cobb et al. 2004; Malesević et al. 2004; Thomson et al. 2004), and GRB 060218/SN 2006aj (Campana et al. 2006; Cobb et al. 2006; Mirabal et al. 2006; Modjaz et al. 2006; Pián et al. 2006; Sollerman et al. 2006; Soderberg et al. 2006). All of the four SNe are among a special class of Type Ic, called the broad-lined SNe indicative of a very large expansion velocity (Iwamoto et al. 1998; Mazzali et al. 2003; Della Valle 2006; Woosley & Bloom 2006; and references therein).

All the above four GRBs are nearby GRBs, among which GRB 030329 is the farthest (at z = 0.17). Observing SN signatures in high-redshift GRBs is difficult, since by selection effects the observable GRBs at high redshift are bright and hence the underlying SNe are easily over-shone by the GRB afterglows. Despite this challenge, a handful of GRBs have shown rebrightening and flattening in their late optical afterglows, which can be interpreted as the emergence of the underlying SN lightcurves (Bloom et al. 1999; Zeh, Klose & Hartmann 2004; Soderberg et al. 2005; Bersier et al. 2006). A systematic study on the GRB afterglows with this approach suggests that all long-duration GRBs are associated with SNe (Zeh, Klose & Hartmann 2004).

However, exceptions to the GRB-SN connection exist. Extensive observations of two nearby long GRBs, 060614 at z = 0.125 and 060505 at z = 0.089, had not detected SNe associated with them down to limits fainter than any SN Ic ever observed (Della Valle et al. 2006; Fynbo et al. 2006; Gehrels et al. 2006). This has been considered to be a challenge to the standard GRB classification scheme based on burst durations (Zhang 2006; Watson et al. 2007).

On the other hand, whether a normal (not broad-lined) core-collapse SN is associated with a GRB or a GRB-like event is uncertain. Considering the fact that GRBs are beamed so that many of them may have been missed by us, people have proposed to look for the GRB signature in nearby SNe by observing the late brightening in radio emissions of nearby SNe as expected when the GRB ejecta are slowed down and the radio emission becomes more or less isotropic (Paczynski 2001; Levinson et al. 2002; Granot & Loeb 2003). However, late-time radio observations of 68 local Type Ibc SNe, including six events with broad optical absorption lines, have found none exhibiting radio emission attributable to off-axis GRB jets spreading into our line of sight (Soderberg et al. 2006a). This leads to a severe constraint on the fraction of SNe Ibc associated with normal GRBs.

With the four spectroscopically confirmed pairs of GRBs/SNe, a relation between the peak spectral energy of GRBs and the maximum bolometric luminosity or the mass of 56Ni in the ejecta of the underlying SNe was derived by Li (2006). A remarkable conclusion inferred from the relation was that “if normal Type Ibc SNe are accompanied by GRBs, the GRBs should be extremely underluminous in the gamma-ray band despite their close distances. Their peak spectral energy is expected to be in the soft X-ray and UV band, so they may be easier to detect with an X-ray or UV detector than with a gamma-ray detector.” (Li 2006, page 1302). For several SNe Ibc that are not as luminous as SN 1998bw, the ‘expected GRB’ derived from the relation has a peak spectral energy in the range of 0.01–1 keV, and a total energy 1034–1036 erg in the energy band 1–10000 keV. It appears that XRF 080109 and SN 2008D agree with the relation (Section 4).

The paper is arranged as follows. In Section 2 the analysis of the XRT data is presented. In Section 3 it is argued that the X-ray transient 080109 cannot be interpreted as a SN shock breakout event. Section 4 shows that the most natural explanation of the nature of the transient 080109 is that it is a faint XRF with a very soft spectrum. In Section 5 models for producing faint and soft XRFs by a normal core-collapse SN are discussed. In Section 6 summary and conclusions are drawn, and future observational strategies are proposed.

2 DATA REDUCTION

The XRT software was used to extract the lightcurve and the spectrum of the X-ray transient 080109 in the XRT energy band 0.3–10 keV from the Level 2 event data file (in Photon Counting mode) downloaded from the 
Swift online archive.

The lightcurve has a FRED (Fast Rise and Exponential Decay) shape and a duration ~ 600 s. Although the X-ray emission was already in progress when the observation began and hence the start time of the burst is uncertain, from the shape of the lightcurve it is expected that the start time of the burst should not be too much earlier than the start time of observation (see, e.g., Fig. 1 of Soderberg et al. 2008).

In extraction of the source and background spectra over a time interval of 600 s containing the burst and beginning at the start time of observation, only events with grades 0–4 (i.e., single and double pixel events) were selected in order to achieve better spectral resolution. A fit of the King function to the point spread function (PSF) of the image showed that the core region with a radius of three pixels was piled up, so the core region was removed from the analysis. Then the source region where the spectrum was extracted was an annular aperture with an inner radius of four pixels (9.4″) and an outer radius of 30 pixels (71″), centered at the source position. The background region was defined as
Figure 1. Fit of the X-ray spectrum (0.3–10 keV) of XRF 080109 by an absorbed double blackbody model (blue line). The best fit is given by \( N_H = 4.7 \times 10^{21} \text{ cm}^{-2} \), \( T_1 = 0.36 \text{ keV} \) (green line), and \( T_2 = 1.24 \text{ keV} \) (magenta line). The reduced chi-square of the fit is \( \chi^2 = 0.65 \), with 16 degrees of freedom.

3 IS THE TRANSIENT 080109 A SUPERNOVA SHOCK BREAKOUT EVENT?

The X-ray spectrum of the 080109 transient can be fitted with a power law (Section 2). No blackbody component is required. A characteristic feature of SN shock breakout is a blackbody-like spectrum \citep{Imshennik1983, Matzner1999}. Hence, the transient event 080109 is not likely to be a SN shock breakout event.

However, as shown in Section 2 the spectrum can be equally well fitted with a model consisting of two blackbody components \citep[Fig. 1]{11.3.1}. Now let us check if one of the two blackbody components might arise from the SN shock breakout event.

From the duration of the event and the bolometric total energy of each blackbody, the average bolometric luminosity and hence the average photosphere radius of each component can be derived. For the softer component \( (T_1 = 0.36 \text{ keV}) \), the radius is \( R_{\text{ph}} \approx 0.074 R_\odot \). For the harder component \( (T_2 = 1.24 \text{ keV}) \), the radius is \( R_{\text{ph}} \approx 0.0062 R_\odot \). Both are much smaller than the solar radius.

The underlying SN of the event, SN 2008D, was initially classified as Type Ib by \citep{Modjaz2008, Valenti2008}. This indicates that the progenitor star should be a Wolf-Rayet star, which usually has a radius of several solar radii. SN shock breakout occurs at a radius near the stellar surface \citep{Imshennik1989, Matzner1999, Tan2001}, or the photospheric radius if the star is surrounded by an intense stellar wind \citep{Lian2007}. Hence, the above results on the photospheric radius of the blackbody emission indicate that neither of the two blackbody components originates from the shock breakout event.

From the derived photospheric radii, a limit on the expansion speed of the blackbody photosphere can be estimated. Assume that the average photospheric radius corresponds to a time of 100 s after the explosion. Then, for the softer blackbody component, the photospheric speed \( v_{\text{ph}} \lesssim 0.0017c \) (where \( c \) is the speed of light). For the harder blackbody component, the photospheric speed \( v_{\text{ph}} \lesssim 0.00015c \). These speeds are non-relativistic, contrary to the prediction that shock breakout from a compact Wolf-Rayet star is mildly relativistic \citep[with a shock breakout velocity \( \gtrsim 0.3c \),][]{Tan2001, Lian2007}.

The duration of the X-ray transient 080109 is \( \approx 600 \text{ s} \), which is also much larger than that predicted for shock breakout in SNe Ib. Hence, we conclude that the X-ray transient 080109 is not a SN shock breakout event.
4 TRANSIENT 080109 AS AN X-RAY FLASH FROM A NORMAL CORE-COLLAPSE SUPERNOVA

Having shown that the X-ray transient 080109 is not a SN shock breakout event, one is left with two alternative interpretations about the nature of the transient: (1) It is a low-luminosity XRF [Berger & Soderberg 2008; Xu et al. 2008]; (2) It is a flare in the X-ray afterglow of a GRB (Burrows et al. 2008).

The transient object happened to be in the BAT field of view in two previous Swift observations (of BZQ J0618+4620 beginning at 13:04:12.33, and of SN 2007ax beginning at 13:12:24.5 UT on 9 Jan 2008). BAT did not trigger during either of the two observations. An examination of the BAT data from the direction of NGC 2770 during those observations shows no sign of emission in the BAT energy range 15–150 keV, with a fluence upper limit of \( \sim 1.0 \times 10^{-7} \) erg cm\(^{-2}\) in a period of half an hour before the start of observation of the transient 080109 (Burrows et al. 2008). In addition, the UVOT lightcurve of the transient closely resembles an early stage UV-optical lightcurve of a GRB (e.g., GRB 060218), rather than a UV-optical afterglow lightcurve during the late declining stage. Hence, the interpretation of the transient event as a flare in the X-ray afterglow of a GRB is also ruled out.

An additional evidence supporting an XRF interpretation of the transient 080109 is in the shape of the X-ray lightcurve after the prompt emission phase. At the end of an exponential decay, the X-ray lightcurve breaks to a power-law decay with an index \( \sim -1.1 \) up to \( t \approx 30000 \) s from the start of observation, which is a characteristic of typical GRB afterglows (Xu et al. 2008).

Based on the above arguments, I conclude that the transient event 080109 in NGC 2770 is a soft XRF, and XRF 080109/SN 2008D well fits the framework of the GRB-SN connection.

XRF 080109 is more under-luminous than the previous most under-luminous burst, GRB 980425, by about two orders of magnitude. The spectrum of XRF 080109 is also softer than that of GRB 980425. During the XRT observation of XRF 080109 which lasted over 1000 s, the BAT fluence upper limit is \( 8.9 \times 10^{-8} \) erg cm\(^{-2}\) in 15–150 keV (Burrows et al. 2008). Extrapolation of the power-law spectral fit in Section 2 to 15–150 keV leads to a fluence of \( 3.4^{+6.3}_{-2.3} \times 10^{-8} \) erg cm\(^{-2}\), marginally consistent with the BAT upper limit.

Due to the limit in the number of photon counts (433 in total after the piled-up core region being removed) and the small range of energy covered by XRT (0.3–10 keV), a reliable constraint on the peak spectral energy cannot be obtained from the XRT data alone. However, the fact that the XRT spectrum of XRF 080109 can be fitted by a single power-law with a photon index \( \Gamma \approx 2.3 \) suggests that the peak spectral energy \( E_{\text{peak}} \) is less than 0.3 keV. A lower limit on the value of \( E_{\text{peak}} \) can be obtained from the UVOT observation during the prompt phase of XRF 080109. The specific flux density in the UBV band (at \( \sim 3 \) eV) during the prompt phase is \( F_{\nu} \ll 9.0 \times 10^{-6} \) \( \mu \)Jy (Immler et al. 2008; Soderberg et al. 2008). According to the synchrotron model for GRB emissions (Sari, Piran & Narayan 1998), \( F_{\nu} \propto \nu^{\alpha} \) with \( \alpha \approx 1/3 \). Then, combination with the power-law fit to the XRT spectrum leads to a constraint on \( E_{\text{peak}} \): \( E_{\text{peak}} > 0.037 \) keV. Hence we have \( 0.037 \) keV \( < E_{\text{peak}} < 0.3 \) keV.

The power-law spectral fit leads to a total isotropic-equivalent energy \( E_{\text{iso}} = 1.3^{+6.5}_{-0.7} \times 10^{46} \) erg in 1–10000 keV in the rest frame of the burst. This value of \( E_{\text{iso}} \), together with the constraint on the peak spectral energy obtained above, makes XRF 080109 agree with the \( E_{\text{iso}}-E_{\text{peak}} \) relation of Amati (2006) (see Fig. 2). Alternatively, from the value of \( E_{\text{iso}} \) for XRF 080109, the Amati relation implies that the peak spectral energy of XRF 080109 should be \( E_{\text{peak}} \approx 0.12^{+0.23}_{-0.09} \) keV, in good agreement with the constraint inferred from the XRT and UVOT data.

The bolometric lightcurve of SN 2008D in the early stage was derived from the UVOT data and modeled by Soderberg et al. (2008). The peak of the lightcurve occurred at about 20 day after the explosion, with a peak bolometric magnitude \( \approx -16.65 \) (corresponding to a maximum bolometric luminosity \( \approx 1.4 \times 10^{42} \) erg s\(^{-1}\)). Fitting the lightcurve by an analytic model of SN emission powered by the radioactive decay of \( ^{56}\text{Ni} \) and \( ^{56}\text{Co} \) yielded a \( ^{56}\text{Ni} \) mass synthesized in the explosion between 0.05 and 0.1M\(_{\odot}\) (Soderberg et al. 2008). These results, together with the peak spectral energy of XRF 080109 derived from the XRT and UVOT data, indicate that XRF 080109/SN 2008D agree with the relation between the peak spectral energy of GRBs and the maximum bolometric luminosity or the nickel mass in the ejecta of the underlying SNe derived by Li (2006), as shown in Figs. 3 and 4 (where the central value of \( E_{\text{peak}} \) is 0.12 keV estimated by the Amati relation).
All known nearby GRBs/XRFs with SNe have strong radio emissions, including GRBs 980425, 030329, 031203, 060218, and XRF 020903. Radio emissions have also been detected for XRF 080109/SN 2008D, although not as bright as the other GRB-SNe (Soderberg et al. 2008). The peak radio luminosities at 6 cm ($L_{\nu,6cm}$) of the six GRBs/XRFs are plotted in Fig. 5 versus their average luminosity of the prompt emission in the X-ray and gamma-ray band ($L_{X-\gamma}$). The data suggest a correlation between the radio luminosity and the X-ray/gamma-ray luminosity, i.e., brighter GRBs/XRFs tend to have a larger radio luminosity.

Type Ic SN 1994I and SN 2002ap were also detected in radio band, although no GRBs/XRFs have been found to be associated with them. With the relation between the peak spectral energy of GRBs and the maximum bolometric luminosity of the underlying SNe (or the mass of $^{56}$Ni generated in the ejecta of the underlying SNe), the peak spectral energy of the potential XRFs associated with SN 1994I and SN 2002ap was derived to be 0.07 keV (or 0.12 keV) and 0.016 keV (or 0.19 keV), respectively. Using the Amati relation, the peak spectral energy can be converted to the isotropic-equivalent energy in the 1-10000 keV band. Assuming a duration of 600 s (the same duration of XRF 080109) for these potential faint bursts, the average luminosity of the prompt emission in the X-ray/gamma-ray band can be calculated. The peak radio luminosities of SN 1994I and SN 2002ap and the derived average luminosities of their potential bursts in the X-ray/gamma-ray band are shown Fig. 5 by open circles. It appears that they follow the trend of the $L_{\nu,6cm}$–$L_{X-\gamma}$ relation suggested by the nearby GRBs/XRFs.

5 HOW ARE SPHERICAL GRBS/XRFS PRODUCED?

In the standard collapsar model of long-duration GRBs (MacFadyen & Woosley 1999; MacFadyen, Woosley & Heger 2001), it is assumed that after the core-collapse of the progenitor star a torus is formed surrounding a rapidly rotating black hole. A bipolar relativistic fireball outflow powered either by the accretion energy of the torus or the spin energy of the black hole is generated, and collimated into two oppositely-directed jets moving along the spin axis of the hole. The fireball is presumably highly nonhomogeneous and composed of a number of outward moving shells. The collision between the shells produces the prompt gamma-ray emission, and the collision between the shells and the surrounding medium produces the afterglow emission (the so-called internal/external-shock model, Piran 2004). In this model, collimation of the outflow is essential for avoiding baryon loading and maintaining a large Lorentz factor (> 100).

However, it appears that some GRBs are spherical. An investigation on the relation between the jet opening angle and the peak spectral energy of GRBs revealed that they are anti-correlated (Lamb, Donaghy & Graziani 2002; Li 2006). That is, GRBs with softer spectra have larger jet opening angles i.e. weakly collimated outflows.

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2 A supernova has been claimed being detected in the afterglow of XRF 020903 (Soderberg et al. 2003; Bersier et al. 2006), which is fainter than SN 1998bw by 0.6–0.8 mag at the peak in the R-band. However, the bolometric magnitude could not be obtained due to the lack of data in other filters.
For GRBs/XRFs with a peak spectral energy < 40 keV (in the burst frame), the jet opening angle inferred from the anti-correlation is so large that the burst outflow should be spherical (Li et al. 2006). This is consistent with the radio observation on XRF 020903 ($E_{\text{peak}} \approx 3.4$ keV) and GRB 060218 ($E_{\text{peak}} \approx 4.9$ keV) (Soderberg et al. 2004a, 2006a). XRF 080109 has a spectrum softer than that of XRF 020903 and GRB 060218, hence the outflow of it should also be spherical. This is consistent with the conclusion that SN 2008D has a non-relativistic ejecta as inferred from its radio emission (Soderberg et al. 2008).

Obviously, the standard internal/external-shock fireball model does not apply to GRBs/XRFs with a spherical outflow, since a spherical fireball outflow cannot avoid baryon loading efficiently: it must pass through the dense SN ejecta. Then, an unavoidable result of a spherical GRB/XRF is that the outflow which produces the burst and the afterglow cannot have a very large Lorentz factor. Due to the loss of energy to the SN ejecta, the burst would be very sub-energetic compared to normal GRBs. In other words, a spherical GRB/XRF would have a low luminosity and soft spectrum, and be at most mildly relativistic.

Whether a spherical explosion can produce a GRB-like event is a question. The GRB fireball is trapped inside the heavy SN envelope so the energy of it may well be dissipated by the SN envelope without producing a GRB/XRF. However, two possible scenarios for producing a GRB/XRF from a spherical configuration can be imagined.

**Scenario A.** When a light fluid is accelerated into a heavy fluid, which is just the case of a spherical GRB explosion as outlined above, the Rayleigh-Taylor instability occurs (Drazin & Reid 2004). The Rayleigh-Taylor instability has been proposed as a mechanism for driving SN explosion (Buchler, Livio & Colgate 1986, Smarr et al. 1981), and a mechanism for the mixing of elements in SN explosion (Hachisu et al. 1990, 1991; Mueller & Janka 1997). In the case of a spherical GRB/SN explosion, the GRB fireball may emerge from the SN envelope through the Rayleigh-Taylor instability, then produce a GRB/XRF through either the internal-shock or the external-shock interaction.

**Scenario B.** The initial GRB fireball is killed by the SN envelope and the fireball energy is added to the SN explosion energy. A small fraction of the outer layer of the SN envelope is accelerated by the enhanced SN shock wave to a mildly relativistic velocity and generates a low-luminosity GRB/XRF via interaction with surrounding matter. This GRB-production mechanism through acceleration of the SN outer layer has been proposed by Matzner & McKee (1999) and Tan et al. (2003) for explaining the prompt emission of GRB 980425. Applying the formulae for this mechanism (Tan et al. 2003) to SN 2008D, with an assumption of the SN explosion energy $E_{\text{in}} \approx 3 \times 10^{51}$ erg, the ejected mass $M_{\text{ej}} \approx 4M_{\odot}$ (Soderberg et al. 2008), and the progenitor mass $M_{\star} \approx 6M_{\odot}$, a total kinetic energy $\approx 4 \times 10^{49}$ erg is obtained for ejecta with a velocity $> 0.5c$. This energy is enough to account for the total X-ray energy emitted by XRF 080109. However, this mechanism is not able to explain GRB 060218, which has a total isotropic energy $\approx 6 \times 10^{49}$ erg emitted in X-ray/gamma-ray, exceeding the predicted kinetic energy by three orders of magnitude [with $E_{\text{in}} \approx 2 \times 10^{53}$ erg, $M_{\text{ej}} \approx 2M_{\odot}$, and $M_{\star} \approx 3.3M_{\odot}$ adopted from Mazzali et al. (2006)].

### 6 SUMMARY AND CONCLUSIONS

The X-ray transient event 080109 in NGC 2770 is the first-ever X-ray flash discovered in a normal core-collapse supernova. It emitted an energy of $E_X \approx 1.3 \times 10^{46}$ erg in the Swift XRT’s 0.3–10 keV band in a duration of $\sim 600$ s. The XRT spectrum of XRF 080109 is well fitted by an absorbed power-law model with a photon index $\approx 2.3$. In combination with the upper limit of the UVOT observation during the prompt emission phase, the XRT spectral fit leads to a constraint on the peak spectral energy of XRF 080109: 0.037 keV $< E_{\text{peak}} < 0.3$ keV. The total isotropic-equivalent energy in 1–10000 keV in the rest frame of the burst is $E_{\text{iso}} \approx 1.3 \times 10^{46}$ erg. With the above values of $E_{\text{iso}}$ and $E_{\text{peak}}$, XRF 080109 is consistent with the Amati $E_{\text{iso}}-E_{\text{peak}}$ relation.

Although the XRT spectrum of XRF 080109 can also be fitted with an absorbed double blackbody model, the photospheric radius derived from the luminosity and the temperature of each blackbody component rules out a SN shock breakout interpretation for the burst. For SN shock breakout from a Wolf-Rayet progenitor star, the radius where the shock breakout occurs is expected to be not smaller than...
The detection of an XRF in a normal core-collapse SN extends the connection between GRBs/XRFs and SNe. It may suggest that every Type Ibc (maybe Type II also) SN has a GRB/XRF associated with it. If this is true, events like XRF 080109 would occur at a rate comparable to that of SNe Ibc, \( \sim 10^{-3} \) yr\(^{-1} \) in an average galaxy (Podsiadlowski et al. 2004).

For a normal core-collapse SN that is not as bright as SN 1998bw, it is expected that the XRF associated with it has a spectrum peaked in the UV to X-ray band and total energy of \( 10^{44} - 10^{48} \) erg (Li 2006). A wide-field soft X-ray telescope devoted to the detection of soft X-ray flares will be very fruitful in discovering these very soft XRFs. The detection of them is very important for understanding the nature of the GRB-SN connection, the emission mechanism of low-luminosity XRFs, and the explosion mechanism of core-collapse SNe.

The design and launch of such a telescope is also important for detecting other three types of events: (1) Shock breakout in SNe Ibc (Li 2007a), which is the first observable electromagnetic signal from a core-collapse SN and should occur ahead of the XRF; (2) Thermal precursors of normal GRBs (Li 2007b), the detection of which will give us a chance to obtain a complete multi-wavelength observation on GRBs starting from the prompt emission phase (e.g., Cenko et al. 2006); (3) Bright GRBs at very high redshift \((z > 10)\) whose peak spectral energy is shifted to the soft X-ray range by the cosmic redshift effect.

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