Swift Observations of X-ray supernovae

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ABSTRACT
We present a result of X-ray supernovae (SNe) survey using the Swift satellite public archive. An automatic searching program was designed to search X-ray SNe among all of the Swift archival observations between November 2004 and February 2011. Using the C++ program, 24 X-ray detectable supernovae have been found in the archive and 3 of them were newly-discovered in X-rays which are SN 1986L, SN 2003lx, and SN 2007od. In addition, SN 2003lx is a Type Ia supernova which may be the second X-ray detectable Type Ia after SN 2005ke (Immler et al. 2006). Calibrated data of luminous type Ib/c supernovae was consistent to the X-ray emission model done by Chevalier & Fransson (1994). Statistics about the luminosities and hardness ratio have been done to purpose of getting the X-ray emission features of the X-ray supernovae. The results from this work help investigating the X-ray evolution of SNe and developing similar X-ray SNe surveys in various X-rays missions.

Key words: supernova remnants supernovae: individual (SN 1986L, SN 2003lx, SN 2007od, X-ray SNe)

1 INTRODUCTION

1.1 X-ray Supernovae
Supernovae (SNe) are stellar explosions which are luminous in various frequencies of electromagnetic wave. Nowadays, the detection rate of SNe in Optical is about few hundreds per year, while number of SNe detection in X-rays are still rare which is less than 50 detections in total. There are two kinds of X-ray emission mechanisms in SNe which are circumstellar-shock interaction or shock breakout. In shock breakout case, shock breakouts envelope of the progenitor which emits strong X-rays in soft band for a short period of time, says minutes. X-ray transient XRO 080109 or SN 2008D located in NGC 2770 (see Soderberg et al. 2008) is the only case discovered. In circumstellar interaction, the X-ray emission is relatively stable which can be last for few years. Most of the radiations come from the explosion shock wave pair (i.e. “forward shock” and “reverse shock”). When shock from the SN center interacts with circumstellar matter (CSM) deposited by stellar wind from the progenitors/progenitors’ companion star, X-ray photons are produced due to thermal, inverse Compton and synchrotron emissions (Immler et al. 2006; Chevalier & Fransson 2006). According to the circumstellar interaction model by Chevalier & Fransson (1994), cooling shell and forward/reverse shocks pair are formed as the ejecta collides with the CSM. In most cases, the forward shock heats up the CSM to emit hard X-ray ($\gtrsim 10$ keV) while the reverse shock interacts with the ejecta to emit soft X-ray ($\lesssim 5$ keV). In the early time, the X-ray opaque cool dense shell between the shocks blocks the soft X-ray from the reverse shocked region. After several days or weeks, the expanding cool shell becomes optically thin which allows the pass through of the soft X-ray. Since there is a relatively high density in the reverse shocked region, soft X-ray is strong and therefore dominates the entire X-ray emission.

One of the oldest X-ray supernova detected was SN 1970G by a Chandra deep image of M101 in 2005, 35 years after the explosion (Trümper 2008). The luminosity of this SN was $\sim 10^{37}$ erg s$^{-1}$ in 0.3–2 keV which is consistent with a mass loss rate of $2.6 (v_w/10$ km s$^{-1}) (M_C/yr)$ (Immler et al. 2006). Recent study indicated that there were even older X-ray SNe: SN 1941C, SN 1959D and SN 1968D (Soria et al. 2008) with X-ray luminosity around $10^{37} - 38$ erg s$^{-1}$ in energy range 0.3–8 keV which were detected by Chandra. These old supernovae are important because they fill up the black box between old and young phases of a supernova remnant.

In this work, X-ray telescope (XRT) on Swift was used for searching X-ray SN candidate from different evolution phases. As the Swift archival data is plentiful (over 30 observations in different field everyday), it is a suitable place to do such X-ray SNe survey. Total 24 X-ray SNe have been detected in this survey. 3 of them are newly-discovered, i.e. SN 1986L, SN 2003lx and SN 2007od. Scientific statistical results of this survey are presented in §2.3 and individual studies of some candidates are discussed in §3.
2 RESULTS AND DATA ANALYSIS

2.1 Searching Method

There are over 5000 SNe have been optically discovered since 1885 which were recorded in detail in the Center for Astrophysics (CfA) archive. Since the sample size of survey target is so large, an automated program was developed to screen all Swift archival data in photon counting mode in the period November 2004 to February 2011 and detect if there is any X-ray SNe in the field. Here gives a brief idea about how the program was working.

Firstly, we developed a local Swift database by downloading all old archival data from the Swift public archive and then using a time-based job scheduler cron to update fresh calibrated X-ray observations to the database at every midnight. Since the file size of a full data set (i.e. auxiliary files, UVOT data and etc) is large which is usually larger than 10 Mb per observation in size, so only X-ray event files which contain information of arrival photons were downloaded to minimize time and computer resources required. All observations in the database were classified into groups according to their aim points.

Afterward, A list which contains all detected SNe positions was extracted and updated from CfA. The program then did positional matching between the the list and the database. Since the real field of view of Swift is 23.6 × 23.6, we set the critical separation to be half length of the diagonal r = 16.7. Once the angular separation between a observation and a SN is less than the critical value, the existence of the corresponding SN in the field of view is confirmed.

For observations that contain SN/SNe in their fields of view, full set of data were downloaded. Observations that belong to the same SN were merged by xselect to optimize the signal to noise ratio and a corresponding X-ray image in energy range 0.3 to 10 keV was extracted. All extracted images were then processed by wavdetect of CIAO to detect all X-ray sources in the field. We set the wavelet scales to be a series from 2 to 8 increasing by a factor of \( \sqrt{2} \), (i.e. 2.0, 2.828, 4.0, 5.657, 8.0). In order to detect those X-ray sources with low counts, the values of the signal and background thresholds were set to \( 5 \times 10^{-6} \). In addition, exposure maps generated by xrtexpmap were used to correct the variation of effective area throughout the image.

According to the pointing accuracy and the angular resolution of Swift XRT, a box search of size 10′′ was used to find any positional coincidence between the corresponding SN and sources in the wavdetect source list. Sources with such coincidences became X-ray SN candidate and went through another 10′′ box search in SIMBAD to do source identification. In case a candidate consists of 1 or more non-supernova identifications, it may be considered to be contaminated by the nearby sources and would be eliminated from the candidate list.

Finally, soft band (0.3–1.1 keV), median band (1.1–2.0 keV) and hard band (2–10 keV) images were extracted from the event files and wavdetect with the above parameters were applied to each band images to check the count rates of each band and hardness ratios of the X-ray SN candidates.

2.2 Justification of the searching method

The ASDC Swift-XRT Simulator was used to simulate Swift observations of series of fake X-ray sources. The simulated observations were then processed by the searching routines discussed to give blind searches of the X-ray sources. Percentage of sources recovered should be a key parameter for justifying effectiveness of the program. In this test, an index 2 power law with hydrogen column density \( n_H = 2.17 \times 10^{20} \text{cm}^{-2} \) model was used to generate 64 X-ray sources in different locations in image. We simulated their Swift observations with exposure times 2000 seconds and 5000 seconds. In 2000 seconds simulation, 78% of the X-rays sources were detected by the program while all X-ray sources were correctly identified and only got 3 wrong identifications for the 5000 seconds case.

2.3 Searching Result

24 X-ray SNe candidates were found in the Swift public archive using our program in the period between November 2004 and February 2011, including 14 Type II, 9 Type Ib/c and 1 Type Ia X-ray SN candidates (see Table 1). Many candidates have been previously studied including SN 1978K in NGC 1313 (Schlegel et al. 1999), 1993J in M81 (Chandra et al. 2009) and etc. We compared our result with the previous publications of Swift and found that SN 2005ke, 2008M, 2008ax, 2008ij, 2009gj, 2010F, 2010jl, 2010jr (Immler et al. 2006, 2008, 2009gj, 2010jl) were missing in our list. The reason was mainly believed due to the different approaches of the SN/source detections. The general X-ray SNe searching methods are targeted searches while a blind search method was used in this work. The latter could be done in an automatic way easily. In order to due with a 5 years database (about fifty thousand observations) automatically, blind search approach was used in this project and it was supposed to be the major reason why there is a slightly difference between the results. Indeed, two of the above missing SNe, SN 2010jl and 2010jr, were found in the out blind search. However, they are too close to the host galaxies, so SN 2010jl was heavily contaminated by the galaxy and SN 2010jr is very hard in spectrum which is likely to be something else (i.e. emission from its host galaxy).

1 http://www.cfa.harvard.edu/iau/lists/Supernovae.html

2 http://www.asdc.asi.it/simulator/swift/
Figure 1. The XRT images of energy band 0.3–10 keV of the "missing" Swift X-ray supernovae. The green ellipses show the sources detected by \textit{wavdetect} in this work while the red crosses show the corresponding SN locations.
| SN Name | SN RA | SN DEC | OBS DATE (UT) | OBS END (UT) | EXP (s) | SRC RA | SRC DEC | SEP (arcsec) | SIGN (sigma) |
|---------|------|--------|---------------|--------------|--------|-------|--------|-------------|-------------|
| SN 1970G | 14 03 00.83 | +54 14 32.8 | 2005-01-20 01:23:34 | 2007-04-19 10:26:56 | 65481 | 14 03 00.43 | +54 14 32.1 | 4.1 ± 1.8 | 3.50 |
| SN 1978K | 03 17 38.62 | -66 33 03.4 | 2006-02-03 22:56:19 | 2008-12-20 02:42:58 | 49940 | 03 17 38.66 | -66 33 02.0 | 1.4 ± 0.6 | 70.92 |
| SN 1979C | 12 22 58.58 | -15 47 52.7 | 2005-11-06 16:00:55 | 2006-03-29 15:15:58 | 57636 | 12 22 58.59 | -15 47 47.9 | 4.8 ± 0.9 | 8.60 |
| SN 1986L | 04 17 29.40 | -62 47 04.0 | 2005-08-10 02:45:26 | 2007-12-12 16:42:57 | 50474 | 04 17 29.19 | -62 46 58.9 | 6.0 ± 1.3 | 14.83 |
| SN 1987A | 05 35 28.01 | -69 16 11.6 | 2005-01-24 01:09:05 | 2006-03-29 05:48:56 | 35728 | 05 35 28.07 | -69 16 10.8 | 1.1 ± 0.3 | 134.90 |
| SN 1993J | 09 55 24.78 | +69 01 13.7 | 2005-04-21 00:47:46 | 2011-02-17 14:35:58 | 293723 | 09 55 24.64 | +69 01 13.6 | 2.0 ± 0.6 | 31.53 |
| SN 1996cr | 14 13 10.05 | -65 20 44.8 | 2007-03-23 06:08:28 | 2009-11-16 22:54:55 | 18492 | 14 13 10.04 | -65 20 44.4 | 0.4 ± 0.5 | 35.33 |
| SN 2003Ix | 16 19 21.65 | +41 05 23.8 | 2008-01-10 20:39:16 | 2008-01-14 22:52:57 | 13810 | 16 19 21.70 | +41 05 25.7 | 2.1 ± 1.2 | 17.20 |
| SN 2005ip | 09 32 06.42 | +08 26 44.4 | 2007-02-14 01:57:14 | 2009-11-19 05:28:57 | 25304 | 09 32 06.44 | +08 26 44.8 | 0.5 ± 0.5 | 32.94 |
| SN 2005kd | 04 03 16.88 | +71 43 18.9 | 2007-01-24 00:56:52 | 2008-08-21 22:44:58 | 18168 | 04 03 17.19 | +71 43 19.2 | 4.0 ± 2.0 | 12.90 |
| SN 2006aj | 03 21 39.66 | +16 52 02.1 | 2006-02-18 05:13:38 | 2010-12-15 23:13:57 | 357796 | 03 21 39.69 | +16 52 00.7 | 1.4 ± 0.2 | 87.06 |
| SN 2006bp | 11 53 55.74 | +52 21 09.4 | 2006-04-10 12:51:21 | 2007-03-31 22:10:56 | 87892 | 11 53 55.84 | +52 21 13.3 | 4.0 ± 1.2 | 3.51 |
| SN 2006jc | 09 17 20.78 | +41 54 32.7 | 2006-10-13 16:10:14 | 2011-01-04 22:02:56 | 202441 | 09 17 20.90 | +41 54 37.6 | 4.9 ± 0.4 | 34.98 |
| SN 2006jd | 08 02 07.43 | +48 31.5 | 2007-11-16 17:35:21 | 2010-06-09 03:07:56 | 69347 | 08 02 07.36 | +48 31.7 | 0.7 ± 0.4 | 39.68 |
| SN 2007od | 23 55 48.68 | +18 24 54.8 | 2007-11-05 16:13:08 | 2008-08-23 19:02:56 | 65929 | 23 55 48.69 | +18 24 52.1 | 2.7 ± 1.3 | 4.21 |
| SN 2007uy | 09 09 35.40 | +33 08 20.1 | 2008-01-06 00:33:07 | 2008-09-21 23:01:55 | 334518 | 09 09 35.02 | +33 08 20.2 | 0.0 ± 0.3 | 11.48 |
| SN 2008bo | 18 19 54.41 | +74 34 21.0 | 2008-04-04 14:54:02 | 2009-02-14 23:05:57 | 383873 | 18 19 54.60 | +74 34 20.7 | 2.0 ± 0.6 | 34.77 |
| SN 2008D | 09 09 30.62 | +33 08 20.1 | 2008-01-06 00:33:07 | 2008-09-21 23:01:55 | 334518 | 09 09 30.62 | +33 08 20.2 | 0.0 ± 0.3 | 11.48 |
| SN 2008hw | 22 39 50.39 | -49 08 49.1 | 2008-10-07 05:26:52 | 2008-10-27 14:00:56 | 188541 | 22 39 50.59 | -49 08 47.0 | 3.1 ± 0.3 | 85.51 |
| SN 2009dd | 12 05 34.10 | +50 32 18.6 | 2009-04-15 14:50:50 | 2009-09-21 23:59:57 | 104014 | 12 05 34.58 | +50 32 20.7 | 7.3 ± 1.0 | 8.85 |
| SN 2009mk | 00 06 21.37 | -41 28 59.8 | 2009-12-17 03:30:58 | 2010-01-30 23:59:57 | 38301 | 00 06 20.72 | -41 29 03.8 | 8.8 ± 1.4 | 1.90 |
| SN 2009nz | 02 26 19.90 | -18 57 09.0 | 2009-11-28 01:02:16 | 2010-06-10 23:44:57 | 470379 | 02 26 20.03 | -18 57 07.2 | 2.6 ± 0.1 | 154.47 |
| SN 2010bh | 07 10 31.80 | -56 15 20.2 | 2010-03-16 21:53:21 | 2010-03-23 20:55:33 | 52488 | 07 10 30.95 | -56 15 17.5 | 12.5 ± 1.2 | 13.18 |
2.4 Data Reduction

We used HEAsoft of version 6.6.2 to do the data analysis. Tasks xrtggle and xrtgglepec were used to extract lightcurves and spectra while the Swift-XRT data products generator (Evans et al. 2001) was used to do some cross-checks sometimes. We binned all spectral products with 20 counts per bin at first. Those binned spectra with 4 or less data points were re-binned with 10 counts per bin. Re-binned spectra with 7 or less data points were re-binned with 5 counts per bin. Spectra with 9 or less data points after 5 counts binning were regarded as low signal to noise which were not used to do model fitting. The background regions were chosen automatically by the tasks. Source-free background regions would be extracted by human sometimes to avoid contamination from some nearby bright X-ray sources or inappropriate background selections at the edges of images. Finally, XSPEC was used to do the spectral fitting to examine physical parameters of the sources. Basically, combinations of simple photon power law model and Raymond-Smith thermal plasma model (Raymond & Smith 1977) were primary models of the analysis. Column densities from Leiden/Argentine/Bonn (LAB) Survey of Galactic HI were used as the Galactic $n_H$, and $n_H$ excess components would be added if necessary. The best fit results of chi-square fittings of 16 X-ray SN candidates are shown in Table 2.

2.5 Properties of X-ray supernovae spectra

In the early phase of the explosion, the strong photosphere radiation is Compton scattered which forms a high energy tail to the photosphere emission. Each photon increases its energy by a factor $\Delta \nu/\nu = 4kT_e/m_e c^2 \gtrsim 1$ where $m_e$ and $T_e$ are electron mass and electron gas temperature, which create a power law spectrum with a photon index $(Fransson 1982; Chevalier & Fransson 2001)$

$$\alpha = \left(\frac{9}{4} \frac{m_e c^2}{k T_e} \ln \tau_e \right) \left(0.9228 - \ln \tau_e\right) \frac{\tau_e}{2} - \frac{3}{2},$$

(1)

where $\tau_e$ is the optical depth to electron scattering behind the circumstellar shock. The typical value is $1 \lesssim \alpha \lesssim 3$ (Fransson 1982). In the diagram, hardness ratios $HR_1 = \frac{M-S}{M+S}$ and $HR_2 = \frac{H+S}{H-S}$ were plotted where $S$ = soft band (S: 0.3–1.0 keV), $M$ = median band (M: 1.0–2.0 keV), and $H$ = hard band (H: 2.0–10 keV). With the reference trends from the Portable Interactive Multi-Mission Simulator (PIMMS) prediction of power law model with various photon indexes and column densities, the diagram shows clearly that the ratio between the hardness $HR_1$ and $HR_2$ are consistent with a power law model of index $\sim 2$ which is consistent the prediction. Spectral fitting results also agreed with the theoretical model. As shown in the Table 2 most of the supernovae (except SN 1993J) show non-thermal components (power law) in their spectra with a mean photon index $\sim 2$ while some spectra also show thermal components with plasma temperatures about $\sim 0.8$ keV. If ages of SNe were taken into consideration, it is clear that older supernovae spectra were fit well with thermal plus non-thermal model while younger supernovae could be satisfied with single power law. One explanation is that non-thermal blast shock emissions dominated the whole X-ray emissions of supernovae which created single power law continuum in the early phase. After years, the shock velocities decreased as the swept-up mass behind the circumstellar shock increased which weakened the non-thermal part, hence the thermal emissions (and the line emissions from elements) started to be significant.

2.6 X-ray Supernovae luminosity

We estimated the X-ray luminosity of the X-ray supernova candidates by the spectral model fitting. For those low signal-to-noise candidates data, the net count rates with power law of photon index 2 were used to estimate the flux using PIMMS. Fig. 3 shows the luminosity function of all candidates. Most of candidates have a luminosity of $\sim 10^{40}$ erg/s in energy band 0.3–10 keV. The most luminous SNe were the GRB-SN associations which have a luminosity of $\sim 10^{44}$ erg/s while the dimmest one was $\sim 10^{36}$ erg/s, which belongs to the SNR 1987A in Large Magellanic Cloud. This wide X-ray luminosity range partly reflects the different stages of evolution of the observed supernovae.

In addition to know more the properties of the SNe progenitors, we used the X-ray luminosities to estimate the CSM density profiles. Chevalier & Fransson (1994) suggested free-free luminosity from reverse shock can be estimated from

$$L_{rev} = \frac{\pi R^2 n_e \lambda n_i \hat{n}_i \Lambda(T) t V}{1 + [2 n_e \lambda \Lambda(T)/(m_p V^2)] t} \text{erg s}^{-1},$$

(2)

where $R$ and $T$ are radius and temperature of the reverse shock, $n_e$ and $n_i$ are the number densities of electrons and ions, $t$ is age of the supernova, $V$ is the shock velocity, $m_p$ is the proton mass and $\Lambda$ is the cooling factor, which can be expressed as $\Lambda = 6.2 \times 10^{-19} T^{-0.6} \text{erg cm}^3 \text{s}^{-1}$ for $10^5 \text{K} <
Table 2. Spectral properties of X-ray SNe candidates

| SN Name               | Distance (Mpc) | $n_H$ (Galactic) (10^{20} cm^{-2}) | $n_H$ (Intrinsic) (10^{20} cm^{-2}) | Photon Index | Plasma Temperature (kT) (keV) | Reduced-$\chi^2$ |
|-----------------------|----------------|-----------------------------------|-----------------------------------|--------------|-------------------------------|-----------------|
| SN 1978K              | 4.5            | 4.07                              | 24$^{+9}_{-8}$                    | 2.7$^{+0.4}_{-0.4}$ | 0.9$^{+0.1}_{-0.1}$            | 1.08            |
| SN 1986L              | 16             | 2.17                              | -                                 | 1.4$^{+0.2}_{-0.2}$ | 0.7$^{+0.2}_{-0.2}$            | 1.25            |
| SN 1987A              | 0.05           | 26.5                              | -                                 | 3.8$^{+0.1}_{-0.1}$ | 0.7$^{+0.2}_{-0.2}$            | 1.42            |
| SN 1993J              | 3.6            | 5.57                              | -                                 | -             | 0.8$^{+0.1}_{-0.1}$            | 1.04            |
| SN 1996cx             | 17             | 55.6                              | -                                 | 1.1$^{+0.2}_{-0.2}$ | -                             | 1.27            |
| SN 2005ip             | 30             | 3.56                              | -                                 | 0.5$^{+0.2}_{-0.2}$ | -                             | 1.16            |
| SN 2005nc/GRB050525A$^b$ | 1780         | 9.07                              | -                                 | 1.7$^{+0.1}_{-0.1}$ | -                             | 1.04            |
| SN 2006aj/GRB060218$^b$ | 136           | 9.37                              | 46$^{+6}_{-10}$                  | 3.8$^{+0.4}_{-0.3}$ | 0.7$^{+0.1}_{-0.2}$            | 1.58            |
| SN 2006jc             | 23.6           | 1.51                              | 15$^{+13}_{-7}$                  | 1.7$^{+0.2}_{-0.2}$ | -                             | 0.81            |
| SN 2006jd             | 79             | 4.52                              | 9.1$^{+31}_{-7}$                 | 1.2$^{+0.2}_{-0.2}$ | -                             | 1.33            |
| SN 2008bo             | 21             | 5.37                              | -                                 | 1.9$^{+0.2}_{-0.2}$ | -                             | 1.16            |
| SN 2008D$^b$          | 27             | 1.7                               | -                                 | 1.5$^{+0.5}_{-0.2}$ | -                             | 0.37            |
| SN 2008hw/GRB081007$^b$ | 1620          | 1.38                              | 56$^{+6}_{-10}$                  | 2.1$^{+0.1}_{-0.2}$ | -                             | 0.84            |
| SN 2009dd             | 13             | 1.83                              | -                                 | 1.9$^{+0.6}_{-0.2}$ | -                             | 1.93            |
| SN 2009ja/GRB091127$^b$ | 239           | 2.8                               | 26                                | 2.4$^{+0.1}_{-0.2}$ | -                             | 1.2             |
| SN 2010bh/GRB100316D$^b$ | 1530          | 7                                 | -                                 | 1.7$^{+0.6}_{-0.2}$ | -                             | 0.82            |

a. Spectrum after outburst was used.  
b. Time average spectra were used.

The XRT net count rate is (2\times10^-3 count/s). By comparing it with a steady flow model, $\rho$cs is consistent to our spectral fitting result and $V_0 = 35000$ km s^-1 were also applied in the calculation. With the relation $\rho_{cs}/\rho_{cs} \approx 0.602 (n - 3)^2$ and the X-ray luminosities of various Type Ib/c SNe, we get a typical picture of Type Ib/c CSM density profile. After comparing it with a steady flow model, $\rho_{cs} = \rho_{cs}$ (Chevalier & Fransson [1994]), the difference between them increases as time/radius raises. If a dropping (i.e. $T \propto t^{-1.3}$) was used, the result then matched perfectly with the prediction of the steady flow model. Although the calculation looks perfect, it is important to notice that the decay rate $T \propto t^{-1.3}$ is not significant to the real situation since there are many assumptions and fixed parameters (i.e. the mass loss and the shock velocity) in the model. The decay rate would be different if other parameters were freed.

3 STUDY OF INDIVIDUAL X-RAY SUPERNOVA

3.1 SN 1986L

SN 1986L was discovered on October 7.6, 1986, with an apparent magnitude of 13.7 in the location of 50° due west of the NGC1559's nucleus (R.A. = 4h17m0, Decl. = -62deg55', equinox 1950.0) [Evans 1986; McNaught 1986]. It is located at NGC1559 where is 16 Mpc from the earth.

Figure 3. The observed X-ray 0.3–10 keV luminosities of supernovae calculated by PIMMS, from SN 1987A (blue shadow) at log10(L0.3–10keV) = 36.3 to SN-GRB candidate SN 2008hw at log10(L0.3–10keV) = 44.2, with an average peak luminosity log10(L0.3–10keV) = 40.3, reflecting partly the different stages of evolution of the observed supernovae.

Schmidt & Kirshner et al. [1994]. SN 1986L was classified as a core-collapse Type II supernova.

Swift did several observations on the field of SN 1986L from 2005-08-10 to 2007-12-12 and detected an excess of X-ray counts (0.3–10 keV) located on 7.1'' from the optical SN position at a 15.4 e level in the 50.5 ks combined image. The XRT net count rate is (2.5 ± 0.3) × 10^-3 count/s. By assuming the column density $n_H = 2.17 \times 10^{20}$ cm^-2 and its distance from the earth was Mpc, the luminosity was approximately (1.8^{+0.2}_{-0.4}) × 10^{46} erg s^-1 in 0.3–10 keV band.

The ROSAT High Resolution Imager (HRI) and XMM-Newton observed at SN 1986L on 1990-06-01 and 2007-04-26 with exposure time 17.5ks and 12.5ks, respectively (Fig. 4).
In the figure, a position coincident X-ray source was observed in all ROSAT, Swift data and XMM-Newton data. The sources seem to have different locations in each mission due to the different position accuracies (i.e. ∼6′′ for ROSAT; ∼5′′ for Swift; ∼2′′ for XMM-Newton). The low exposure time of ROSAT observation brought a low signal-to-noise ratio image which is not much informative. Using the data of XMM-Newton, the luminosity in energy band 0.3–10 keV was estimated which is \( (3.1_{-1.1}^{+0.9}) \times 10^{36} \text{ erg s}^{-1} \) in 2007.

### 3.2 SN 1987A

SN 1987A is one of the most famous and well-known supernovae in astronomical history because it is the only supernova that was detected in neutrino before optical light reached the earth till now. SN 1987A is located in the Large Magellanic Cloud, which is 50 kpc from us. This short distance allows us to resolve the detailed structure of the entire debris in optical. Apart from the optical features, the SN 1987A is distinctive because it is the only Type IIP supernova that was detected in X-rays. It is also the X-ray dimmest supernova (∼10^{36} \text{ erg s}^{-1} in 0.3–10keV) ever detected, which is the result of the short distance between LMC and the earth. (Trümper 2008). The soft band (0.5–2.0 keV) light curve of the SN 1987A in the past ∼10 years (Fig. 5) shows that an exponential increasing trend almost from ∼5500 days after the outburst. This rapid increase was due to the interaction between the blast shock wave and the medium in the inner ring.

**Swift** observed SN 1987A six times between April 2005 and January 2006. Using a double constant temperature plane-parallel shock plasma model (i.e. wabs*(vpshock+vpshock)) with hydrogen column density and elemental abundances from the best fit values of Zhekov et al. (2006), the best fit shock temperatures are 0.41^{+0.10}_{-0.10} keV and 2.87^{+0.60}_{-0.73} keV respectively which are consist with results 0.41^{+0.60}_{-0.25} keV and 3.40^{+0.77}_{-0.66} keV of Zhekov et al. (2006). The estimated luminosity of 0.5–2.0 keV is \( L = 1.40^{+0.04}_{-0.04} \times 10^{36} \text{ erg s}^{-1} \) which is also consistent to the trend of the multi-mission lightcurve of SN 1987A which is shown as Fig. 5.

### 3.3 SN 1993J

SN 1993J was discovered on March 28, 1993 in the nearby spiral galaxy M81 (Ripero & Garcia 1993). It is the most intensively monitored X-ray SN after SN 1987A. The first X-ray observation was done by ASCA 6 days after its discovery. Afterward, the evolution of the SN was monitored by ASCA, ROSAT (6-1800 days); XMM-Newton, Chandra (2500-5500 days); Swift (after 4800 days) in the past 16 years. With the substantial number of complete observations, the entire SN evolution analysis could be performed through spectral fitting.
a rapid enhancement of X-ray flux. As shown in the Fig. 6, the X-ray luminosity of the SN 1993J was decreasing over its life. [Zimmermann et al. (1993)] suggested the luminosity in range of 0.3–2.4 keV decay with \( t^{-4} \) over the first 200 days. With the assumptions of the mass loss rate of the progenitor wind can be expressed as

\[ M = 4\pi\rho_0 r^2. \]

and the luminosity is roughly proportional to square of the density, the density profile index was estimated as \( s = 1.65 \) (Zimmermann & Aschenbach 2003).

The Swift data taken between 2009 and 2011 (Fig. 7) shows the decay rate of the X-ray flux was slowing down. The light curve is almost a constant ??? or ??? with one sigma fluctuation ??? or ??? in that period.

3.4 SN 2007od

SN 2007od was detected by S. Maticic on four unfiltered CCD images taken around Nov. 2.85 UT with the 60-cm f/3.3 Cichocki reflector in the course of the Comet and Asteroid Search Program (PIKA) at Crni Vrh Observatory. The optical position is at R.A. = 23h55m48s.68, Decl. = +18deg24’54.8” [Mikuz & Maticic 2007].

SN 2007od was observed by Swift initially 3 days after the explosion. No significant X-ray signal was detected at the position in the 4.0 ks XRT exposure by that observation (Immler et al. 2007b). After combining with the later observations, there was a X-ray source detected at the SN position with a 5.7\( \sigma \) significance in the merged 58.2 ks XRT data. The detected count rate was \( (4.8 \pm 1.2) \times 10^{-4} \) count s\(^{-1} \) which is corresponding to a flux rate of \( 1.8 \times 10^{-14} \) erg cm\(^{-2} \) s\(^{-1} \) with a power law model of photon index 2. The reason of the deferred X-ray emission is most likely absorption by the cool, dense shell formed by the reverse shock at the early epoch [Chevalier & Fransson 1994; Nynmark et al. 2006].

\[ L_x \propto t^{-(15-6s+sn-2n)/(ns)}, \]

where \( r^{-n} \) is the radial dependence density profile of the SN ejecta and \( s \) is the profile index of (4). By taking a reasonable assumption the progenitor is compact with \( n = 10 \) [Fransson et al. 1993], it gives \( L_x \propto t^{-(4s-5)/(10s)} \). Compare the equation with the observed decline of \( t^{-0.6} \), the value \( s \approx 2 \) which is consistent to the initial interaction of an expanding Type II supernova with a CSM created by mass loss of the progenitor [Chevalier 1982].

4 DISCUSSIONS AND CONCLUSIONS

We have investigated over 6 years archival Swift observations taken from November 2004 to February 2011 and discovered three new candidates (i.e. SN 1986L, 2003lx and 2007od) out of 24 X-ray detectable Swift SNe. It is considerable because there were only \( \sim 40 \) detections of X-ray SNe in the past, we recovered half of them and increased the total detections by \( \sim 10\% \). Furthermore, The automatic selection program developed in this project worked well to select useful supernova data from over thirty thousand observations in the archive. The success of this work ensures the feasibility of other analogous surveys in Swift. It is also promising that
The X-ray luminosity was discovery of the Type Ia X-ray SN candidate, SN 2003lx. Fransson (1982; Chevalier & Fransson 1994).

tios and CSM density profile partly ensure the theoretical features. Even the supernovae of the same type, the varia-
survey lasts for a few more years.

more X-ray SNe detections would be found if this complete matches most of the cases may be a tangible testimony of that. Based on this thought, we have done several statistics and shock wave properties are doubtless to influence the X-ray emissions. It is difficult to find a simply model to satisfy all features of all X-ray SNe spectra perfectly. However, in a macroscopic view, it is still fair to say that most of the X-ray SNe spectra are similar to each other. Power law model matches most of the cases may be a tangible testimony of that. Based on this thought, we have done several statistics on their luminosities, hardness ratios and the CSM density profile. The results show that most of the SN luminosities lie on the $10^{39}$ to $10^{41}$ erg s$^{-1}$. The studies of hardness ratios and CSM density profile partly ensure the theoretical models (Fransson 1982; Chevalier & Fransson 1994).

One of the important contributions of this work is the discovery of the Type Ia X-ray SN candidate, SN 2003lx. The X-ray luminosity was $\sim 4.8 \times 10^{41}$ erg s$^{-1}$ in 0.3–2.0 keV which was inferred by power law of index $\sim 2$ and distance 155 Mpc. The luminosity is high compare to the other Ia SNe which have typical luminosity of a upper limit $\sim 10^{38}$–$10^{39}$ erg s$^{-1}$ (Immler et al. 2006). However, observations taken by ROSAT in 1990 provides a strong evidence that there was no X-ray detection at the SN position before the SN explosion which is consistent to a Type Ia SN emission.

We did some study on the SN 1987A, 1993Jx to monitor their explosions. Basic analysis of the three new SNe were done to see their X-ray properties. In fact, there are still several X-ray SNe potential candidates (for example, SN 1989B and SN 2007ax) which did not show in this paper as their X-ray signals are weak and/or the off-set from SN position are huge. More Observations or better images (by Chandra or XMM-Newton) are expected to confirm these potential candidates.

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**Figure 8.** Swift X-ray lightcurve of SN 2007od in range of 0.3 to 10 keV.
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