Soft and Hard X-rays from YOUNG Stellar Explosions

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“We always find something, eh Didi, to give us the impression We exist?” — S. Beckett
Envelope-Stripped SNe

★ Deepest Limits to Type Ia SNe
Margutti et al., 2014ApJ...790...52M
Margutti et al., 2012ApJ...751..134M

★ First solid detection of X-rays from a SuperLuminous SN
Chandra is observing right now!!!
Margutti et al., in prep

★ The weakest Engine-driven SNe
Margutti et al., 2014ApJ...797..107M
Margutti et al., 2013ApJ...778...18M

★ Massive Envelope Ejection timed with Core-Collapse
(The SN chameleon 2014C)
Milisavljevic, Margutti et al., 2015ApJ...815..120M
Energy partitioning

SNe are an OPTICAL phenomenon

$10^{51}$ erg

$10^{47}$ erg

X-rays/Radio

Ordinary SNe Ibc

Margutti +13, +14, +15, +16; Kamble +13
Energy partitioning

SNe are an OPTICAL phenomenon

Margutti +13, +14, +15, +16; Kamble +13
"It sort of makes you stop and think, doesn't it."
RADIATION from the REMNANT

X-rays from Supernovae

Log Lx

SHOCK BREAK OUT
(R exploding star)

Δt ≈ 2ms
T ≈ 250 keV
E ≈ 3 \times 10^{41} \text{ erg}

Δt ≈ hrs
(@ T0+5hrs)
T ≈ X-rays
E ≈ 10^{46-47} \text{ erg}
L ≈ 10^{44} \text{ erg/s}

< several hrs

SHOCK INTERACTION w. COMPAANION
(R and distance of the companion)

PROGENITORS

SHOCK/JET INTERACTION w. the MEDIUM
(mass-loss of the progenitor)

MASS-LOSS

RADIATION from the REMNANT

COMPACT OBJECT

> 10 years

Log Time
...BUT...
X-rays from Supernovae

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RADIATION from the REMNANT

COMPACT OBJECT

PROGENITORS

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> 10 \text{ years}

Log Lx

Log Time
The BIG questions
(current Areas of Ignorance)

• Stellar Progenitors and their pre-explosion structure
• Mass Loss
• Explosion Mechanism/Source of Energy

![Progenitor of SN 2009ip](image1)

![Eta-Car](image2)
Expected Evolution from Stellar tracks:

- Supergiant
- Wolf-Rayet
  \( \sim 10^4 \cdot 10^5 \text{ yrs} \)
- SN Explosion

[Graph showing the relationship between density and radius over time]

MASS LOSS - Massive Stars
Expected Evolution from Stellar tracks:

Supergiant → Wolf-Rayet → SN Explosion

$\sim 10^4 - 10^5$ yrs

Density vs. Radius
Expected Evolution from Stellar tracks:

Supergiant → Wolf-Rayet ~10^4 - 10^5 yrs → SN Explosion

Radius → Density

MASS LOSS - Massive Stars
Expected Evolution from Stellar tracks:

- Supergiant
- Wolf-Rayet
- SN Explosion

~$10^4$-$10^5$ yrs

Vshock $\sim$ (10-500) Vejection

H-free!!!
Vshock~ (10-500) Vejection

(10-500)t
Core-Collapse

Type I
H-poor

Type II
H-rich

SN

Ib
Ic
Ic-BL
IIn
IIP
IIL
Type I
H-poor

SN2014C

Type II
H-rich

Margutti et al., 2016, Submitted, arXiv: 1601.06806
SN2014C: a normal Ib SN

dist = 15.7 Mpc

Optical Spectrum at max dist = 15.7 Mpc

Bolometric Luminosity

SN 2014C: a normal Ib SN

Milisavljevic, RM+15
Development of H-features with time

Figure 6 shows an enlargement of the day 373 spectrum, which has only narrow components, is a synthetic spectrum of SN 2014C created with SYN++ (Milisavljevic et al. 2012). But in the case of SN 2014C, whereas iPTF13bvn (t = 4 d) shows only narrow components, the day 373 spectrum, the emissions are increasely complex and originate from several distinct regions.

The narrow components are presumably associated with the shock and/or ejecta running into CSM. The intermediate component is associated with the forward shock, and the intermediate component is associated with wind material that is being photoionized by X-rays of the supernova-CSM interaction may have accelerated its velocity.

Figure 4. The spectrum of SN 2014C compared to those of other type Ib supernovae near maximum light. The spectra of SN 2014C and SN 2008D have been corrected for extinction using the spectrum of iPTF13bvn has not been corrected (Cao et al. 2013; Srivastav et al. 2014). The data were originally published in Soderberg et al. (2008; Modjaz et al. 2009), respectively, whereas Srivastav et al. (2014) and were digested in Milisavljevic et al. (2012). Some additional lines are observed including [O III] 5007, [Ne V] 6363, [N II] 6548, 6583 lines having instrumentally corrected for extinction and a complete list of identified parameters are given to the left of each spectrum. Scaling in SYN++ Shed in MILISAVLJEVIC et al. 2015, some additional lines are observed including [O III] 5007, [Ne V] 6363, [N II] 6548, 6583 lines having instrumentally corrected for extinction and a complete list of identified parameters are given to the left of each spectrum. Scaling in SYN++

The strongest constraint on the wind velocity comes from the supernova-CSM interaction may have accelerated its velocity.

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SN2014C-X-rays (soft+hard)

FIRST Hstripped-SN ever detected at hard X-rays!
SN2014C-X-rays (soft+hard)

First H stripped-SN ever detected at hard X-rays!

Rising X-ray Luminosity!

Open Supernova Catalog (~36000 SNe)
https://sne.space/

First H stripped-SN ever detected at hard X-rays!
SN2014C-X-rays (soft+hard)

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R.M+16

0.3–30 keV X-ray Luminosity (erg s⁻¹)

Time since Explosion (days)

SN2014C

FIRST Hstripped-SN ever detected at hard X-rays!
SN2014C - X-rays (soft+hard)

FIRST H stripped-SN ever detected at hard X-rays!

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Expected Evolution from Stellar tracks:

- Supergiant
- Wolf-Rayet (\(\sim 10^4\) - \(10^5\) yrs)
- SN Explosion

\[ L_x \sim t^{-\alpha} \]

H-free!!!

Density

X-rays

Radius
Chandra NuSTAR

$F_{\nu}$ (keV cm$^{-2}$ s$^{-1}$ keV$^{-1}$)

Energy (keV)

$T \approx 20$ keV

NH$\approx 4d22$ cm$^{-2}$
Direct Constraints on the shock dynamics!
Type I SN → Type II SN
Density vs. Radius

H-poor medium
Type I → Type II

H-poor medium

High-density H-rich medium

The spectrum of SN 2014C compared to those of other type Ib supernovae near maximum light. The spectra of SN 2008D (t = 2000 and +2200 km s\(^{-1}\)) and iPTF13bvn (t = 10 d) are identified, as well as high velocity (HV) hydrogen that spans (1 \* 10\(^{-3}\)) - 10 \* 10\(^{-1}\) expansion velocities of (1 \* 10\(^{-4}\)) - 1 \* 10\(^{-1}\) s. Some absorption features dominated by single ions with projected D = (0.75) - (3.0) \* 3.0 + 1.3 \* 10\(^{16}\) \(\pm\) constant.

Figure 6 shows an enlargement of the day 373 spectrum, which has only narrow components, is associated with the shock and/or ejecta running into CSM. The forward shock, and the intermediate component is associated with wind material that is being photoionized by X-rays of the intermediate-width component with a FWHM width of H\(\alpha\) emission features. Several narrow, unresolved emission corrected for extinction and a complete list of identified absorption features.

We interpret emission at later epochs to be dominated by emission local to the supernova-CSM interaction may have accelerated its velocity.

Broad emission centered around the [O\(\text{III}\)] \(\lambda\lambda\) 4959, 5007 lines is seen in our spectra beginning on day 282 and continues to be visible through our last spectrum obtained on day 474. The width of the emission is different than the shocked CSM. Presumably it is emission due to ionization of the pre-shock medium as seen in supernovae many years to decades after core collapse. Broad [O\(\text{III}\)] \(\beta\) emission is normally only seen in supernovae near maximum light. The spectrum of SN 2014C has an upper limit of 300 km s\(^{-1}\) for the unshocked wind velocity.

Beginning with the day 282 spectrum and continuing through the day 373 spectrum, the emissions are increasing, implying complex and originate from several distinct regions. The spectrum of iPTF13bvn has not been corrected (Cao et al. 2014; Milisavljevic et al. 2012). But in the case of SN 2014C, the strongest constraint on the wind velocity comes from absorption lines dominated by single ions with projected D = (0.75) - (3.0) \* 3.0 + 1.3 \* 10\(^{16}\) \(\pm\) constant.

Some absorption features dominated by single ions with projected D = (0.75) - (3.0) \* 3.0 + 1.3 \* 10\(^{16}\) \(\pm\) constant.
$R \sim 5 \times 10^{16} \text{ cm}$

- **H-poor medium**
- **High-density H-rich medium**

- $\sim 1 M_\odot$

- Ejected $\sim 20$-2000 yrs before explosion
Expected Evolution from Stellar tracks:

- Supergiant
- Wolf-Rayet
- SN Explosion

$\sim 10^4 - 10^5$ yrs

H-free!!!
Expected Evolution from Stellar tracks:

Supergiant → Wolf-Rayet → SN Explosion

~$10^4$–$10^5$ yrs

H-free!!!

Density

Radius

Hydrogen

H-free!!!
Why so important?

Mass - Loss

Stellar Structure at Collapse

“Explodability” of a Star
Why so important?

Mass - Loss

Chemical Enrichment of the Universe

Stellar Structure at Collapse

“Explodability” of a Star

Impact our understanding of the Star Formation History of the Universe.
Expected Evolution from Stellar tracks:

Supergiant → Wolf-Rayet → SN Explosion

\[ \text{MASS LOSS} – \text{Massive Stars} \]

\[ \text{SN2014C} \]

\[ 30 \text{ ks} \]
All H-stripped CC-SNe $d < 40$ Mpc $\rightarrow$ 300 ks/yr
**Method of Investigation**

- **Stellar models** (progenitor + environment)
- **Pre-explosion Imaging** (direct mass-loss constraints)
- **Progenitor Detection**
- **Shock Break out** (progenitor)
- **Optical/UV/NIR Monitoring** (ejecta composition, asymmetries, Etot)
- **Radio/X-ray/Gamma-ray** (mass-loss)
  - Chandra, XMM, NuSTAR, Swift, VLA → SKA
- **Galactic SN remnants** (asymmetries, shocks, progenitors)
  - (Energy source, Explosion mechanism, progenitor properties)
  
**Time since Explosion (yr)**

-1000 -100 -10 -1 1 10 100 1000

**Pan-STARRS1, PTF, ASASSN → LSST**

**HST, → EUCLID**
Time since Explosion (yr)

-1000 -100 -10 -1 1 10 100 1000

Stellar models (progenitor+ environment)

Shock Break out (progenitor)

Pre-explosion Imaging (direct mass-loss constraints)

Optical/UV/NIR Monitoring (ejecta composition, asymmetries, Etot)

Radio/X-ray/Gamma-ray
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Chandra, XMM, NuSTAR, Swift, VLA → SKA

Method of Investigation

Progenitor Detection

HST, → EUCLID

Pan-STARRS1, PTF, ASASSN → LSST

(energy source, Explosion mechanism, progenitor properties)
SN2008D
DISCOVERY SPACE

0.3–10 keV Luminosity (erg s⁻¹)

Time (days)

SN shock breakout
SN interaction w. companion

Luminous Blue Variable
Red Super Giant
Wolf-Rayet

BH
NS

Poster by Dan Milisavljevic!
Multi Wavelength Characterization
Mass-loss in evolved massive stars is one of the least understood aspects of stellar evolution, it is relevant to a number of different areas of Astrophysics, it deserves further attention.

Thanks to Chandra, XMM, Swift, NuSTAR for your generous support to our investigation.
“...The END... is where we start from...”

The Little Gidding by T.S. Eliot

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Back up
Super-Luminous X-rays are not for everybody...
SN2008D/XRF080109
Serendipitous Detection by Swift/XRT

Soderberg + 2008

2008 January 7

NGC2770, d=27 Mpc

Swift horizon = 200 Mpc

Duration of ~400 sec
Gamma=2.3 +/- 0.3
NHint=6e21 cm-2

3.5d-10 erg/s/cm2 observed
Ex=2d46 erg
Lpeak=6d43 erg/s
Expected Evolution from Stellar tracks:

Supergiant → Wolf-Rayet → SN Explosion

~$10^4$-$10^5$ yrs

MASS LOSS – Massive Stars

Density → Radius

Hydrogen

H-free!!!
Expected Evolution from Stellar tracks:

Supergiant → Wolf-Rayet → SN Explosion

$\sim 10^4 - 10^5$ yrs

Nuclear Burning Instabilities

1000 yrs
Binary Evolution
Burning Instabilities
MASS LOSS
Nathan’s Review Paper
Non thermal Radio emission Ibc

Radio Luminosity (erg s$^{-1}$ Hz$^{-1}$)

Time since Explosion (days)

PTF11qcj
2007bg
2001em
20014C
2003gk

RM+16

10%
~6.5% [3.5-10%] of Ib/c progenitors go through CE evolution within ~ few 1000 yr before collapse
Non thermal Radio emission Ibc
The PROBLEM

Progenitor System

Type Ia SN explosion

“...The end is where we start from...”

The Little Gidding by T. S. Eliot
Type Ia SN2014J
Host Galaxy: M82, D=3.5 Mpc

Chandra X-ray images

Margutti +14
Thanks to the Chandra Team!!

X-rays from Supernovae

SHOCK BREAK OUT (R exploding star)

COOLING ENVELOPE (R envelope)

SHOCK INTERACTION w. COMPANION (R and distance of the companion)

Successful JET

PROGENITORS

Very early observations (DIFFICULT)

< hours

10-100 days

MASS-LOSS

RADIATION from the REMNANT in engine driven SNe

SOURCE of ENERGY

FUTURE

> 10 years

Faint (DIFFICULT)

Log Lx

Log Time

FUTUERE

ACCRETION onto the progenitor

ACCRETION from the REMNANT in engine driven SNe

Mass-loss of the progenitor

Mass-loss PROGENITORS

Successful JET

SHOCK INTERACTION w. COMPANION (R and distance of the companion)

COOLING ENVELOPE (R envelope)

SHOCK BREAK OUT (R exploding star)

Very early observations (DIFFICULT)

< hours

10-100 days

MASS-LOSS

RADIATION from the REMNANT in engine driven SNe

SOURCE of ENERGY

FUTURE

> 10 years

Faint (DIFFICULT)