25 years of Supernova 1987A
Why are supernovae interesting?

• They are the sources of all heavy elements in the universe
• They regulate the formation of new stars and planetary systems
• They create some of the most extreme environments known to physics – e.g., neutron stars and black holes
Supernova Type II

Core exceeds Chandrasekhar limit, 1.44 M☉. Core collapses.

Protons combine with electrons and form neutrons. Core shrinks.

Neutrons bounce back infalling matter, due to the Strong Nuclear Force.

Shockwave slows down.

Shockwave accelerated by massive neutrino flow. Star is torn apart. 10^51 J of energy released. Explosion brighter than entire galaxy. The remnant is a neutron star or a black hole. Initially 100 billion degrees K hot!
Why is SN1987A interesting?

• It is the brightest supernova since 1604 AD
• It is the nearest (by factor ~50) supernova seen in the last half century
• It is the first supernova to be observed in its entire electromagnetic spectrum (radio to gamma rays)
• It is the first supernova for which we have observed neutrinos
• It keeps on delivering surprises
# HISTORICAL SUPERNOVAE

<table>
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<th>Date (AD)</th>
<th>Type</th>
<th>Magnitude</th>
<th>Discovered by</th>
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<td>I</td>
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<td>393</td>
<td>?</td>
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<td>1604</td>
<td>I</td>
<td>-3</td>
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<td>1987</td>
<td>II</td>
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REMNANTS OF HISTORICAL SUPERNOVAE

SN185 (I)
SN386 (II)
SN393(?)
SN1006 (I)

SN1054 (II) (Crab Nebula)
SN1181(II)
SN1572 (I) (Tycho)
SN1604 (I) (Kepler)
February 23, 1987: Ian Shelton discovers SN1987A
Feb. 23, 1987: Kamiokande experiment detects a flash of neutrinos (total energy \( \sim 0.1 \, M_\odot c^2 \)) \( \Rightarrow \) a neutron star formed
March 20, 1987: we predict that Ginga satellite will detect hard X-rays emerging from SN1987A “in several months”

INSIDE SUPERNova 1987A

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Received 1987 March 20; accepted 1987 April 13

ABSTRACT

We discuss the X-ray, ultraviolet, and infrared spectra that should soon emerge from the recent supernova in the Large Magellanic Cloud. In several months, we may witness a spectacular display of X-rays and UV emission lines and continuum, as the supernova envelope expands to reveal the inner debris of the explosion. We consider two likely scenarios: first, that the debris produces strong gamma rays from radioactive $^{56}$Co, and second, that an X-ray emitting pulsar exists at the center. In the first case, the gamma rays will Comptonize and emerge as a strong 20–30 keV source detectable by the Ginga satellite. In the latter case, a soft X-ray photoelectric cutoff will move to lower energies as the envelope expands. In both cases, the X-rays will deposit a substantial fraction of their energy in excitations of resonance and semiforbidden lines of H I, O I, and other heavy elements. These UV lines scatter repeatedly in the envelope and emerge as emission lines atop a strong continuum due to overlapping lines broadened by expansion. The envelope will likely become molecular, and its spectrum should show H$_2$ UV emission lines. We also predict that infrared echoes will appear as a result of reprocessing of the initial and emergent bursts of optical/UV light by circumstellar grains. The luminosities of these echoes can provide a sensitive test of the mass-loss history of the supernova progenitor.

Subject headings: gamma rays: general — infrared: sources — stars: supernovae — ultraviolet: spectra — X-rays: sources
Beijing University, Sept. 1987: phone call from Tokyo

X-Ray Observation of SN 1987A from Ginga

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(Received 1990 June 20; accepted 1991 January 22)

Abstract

An X-ray light curve of SN 1987A was obtained from Ginga over a 1000-day period since its outburst. X-rays from the SN appear to comprise two separate components: a hard and a soft component. Hard X-rays were first detected in July 1987, reached a maximum near the end of 1987, and declined steadily through January 1989. Later, the hard component has been close to or below the detection limit. A remarkable soft X-ray flare conclusively from SN 1987A occurred in January 1988. In addition, soft X-rays were occasionally observed significantly in the region of SN 1987A.

Key words: SN 1987A; Supernova; X-rays.
Optical Light curve: driven by radioactivity

$\alpha_{56^{Co}} = 0.07 M_{\odot}$

$56^{Co} \rightarrow 56^{Fe} + e^{+} + \gamma$

$t = 111.3$ days

$57^{Co} \rightarrow 57^{Fe} + e^{+} + \gamma$

$t = 391$ days

3 months – 1 year: optical light fades $\sim \exp(-t/111.3 \text{ d})$

– tracks radioactive decay of $^{56^{Co}}$

Optical Light curve: driven by radioactivity

$\Rightarrow M(56^{Co}) = 0.07 M_{\odot}$
t \sim 2 \text{ days}: \text{spectrum looks like hot } (10^5 \text{ K}) \text{ star with rapidly (20,000 km/s) expanding outer atmosphere}

t \sim 50 \text{ days}: \text{spectrum now looks like cool } (3000 \text{ K}) \text{ star with atmospheric expansion velocity } \sim 5000 \text{ km/s}

t \sim 195 \text{ days}: \text{spectrum looks like transparent gaseous nebula (no photosphere). Emission line widths indicate expansion velocity } \sim 2000 \text{ km/s}
December 1987: Kuiper Airborne Observatory detects CO emission bands, and a few months later, strong far-infrared continuum. Implications: temperature of internal debris has dropped below 2000 K, CO molecules and dust grains have formed.
Spectrum evolution -- ultraviolet

July 87 – April 88:
International Ultraviolet Explorer (IUE) telescope observes narrow (FWHM ~ 20 km/s) ultraviolet emission lines. Rise and fall in about 1 year.

Implications:
1) the radiation was coming from circumstellar gas ionized by the supernova outburst.
2) Location about 0.6 light year away from the supernova.
3) Gas was ejected from SN progenitor 20,000 years before the event.
August 1990: We predict that SN debris will strike circumstellar matter by 2006, giving rise to a rapidly brightening source of X-rays, infrared and radio emission.

SUPERNova REMnant 1987A
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Received 1990 August 10; accepted 1990 October 9

ABSTRACT
A dense circumstellar shell, with radius of about 0.5 lt-yr, surrounds SN 1987A. In ≤16 yr after outburst, the expanding debris of SN 1987A will strike this shell. When it does, the hot gas and relativistic electrons resulting from the forward and reverse shocks will radiate X-rays, infrared radiation, and nonthermal radio waves. The remnant of SN 1987A will then become one of the brightest X-ray and radio sources in the LMC. Subject headings: hydrodynamics — nebulae: individual (SN 1987A) — nebulae: supernova remnants — radiation mechanisms — shock waves
April 1994: Newly repaired Hubble Space Telescope images triple-ring system around SN 1987A. Inner ring has radius 0.6 light years.
Crash: birth of SNR1987A

Time-lapse movie of HST optical images 1994 - 2006
Three views of the supernova debris and its shock interaction with the circumstellar ring.
2003 – present: the inner debris is becoming brighter!
Heating of interior is no longer dominated by radioactivity; it’s dominated by X-rays from ring.
April 2010: Herschel Telescope observes luminous source of FIR (250 – 400 mm) emission, implying ~ 0.6 solar masses of cold (~40 K) dust in debris – much more than expected.
May 2009: NASA installs Cosmic Origins Spectrograph (COS) on Hubble Space Telescope. COS development was led by Prof. Jim Green of U. of Colorado.

COS spectrum (March 2011) showing high velocity Lyα and N^{+4} emission from outer debris of SN1987A
May 2012: ALMA (Atacama Large Millimeter Array) tentatively detects CO 1-0 emission line from supernova debris
What have we learned

- SN1987A was formed as a result of the collapse of the core of a massive star, which formed a neutron star (we think!)
- The interior debris of SN is enriched in heavy elements, as expected
- For $t < 16$ years, the light of the SN was dominated by radioactive decay of $^{56}\text{Co}$, $^{57}\text{Co}$, and $^{44}\text{Ti}$.
- The debris is cold ($T < 100$ K). Dust and molecules formed early. Most heavy elements are now in dust grains.
- The SN is surrounded by a triple-ring system of gas that was ejected by the pre-supernova star, 20,000 years before the explosion.
- Some 15 years after the explosion, the outer debris of the supernova struck the inner circumstellar ring. The ensuing shock interaction caused rapid brightening of infrared, optical, and X-ray radiation.
- Relativistic electrons accelerated by the shock interaction caused rapid brightening of radio emission (synchrotron radiation).
- The light from the inner debris is now dominated by heating due to illumination by X-rays from the shock interaction.
Compact object? – not a clue!

Bolometric luminosity
< few hundred $L_\odot$
< 10^{-3} Crab pulsar

The best hope: image compact FIR source with JWST (projected launch date 2018)
Mysteries

• What are the properties of the compact object? Maybe ALMA will resolve a sub-mm central object. Otherwise, wait for the launch of JWST (2018).
• What is the distribution of newly synthesized elements in the interior? Resolve molecular emission with ALMA and JWST.
• What caused the ejection of the triple-ring system? Wait a few years, and X-rays will cause heretofore unseen circumstellar matter to glow.
• How (where) are the relativistic electrons accelerated? Image non-thermal radio emission with ALMA.
Thanks to:

• Yueming Xu
• Ding Luo
• Eli Michael
• Hongwei Li
• Kevin Heng

• Mike Shull
• Peter Sutherland
• Svet Zhekov
• Nathan Smith
• Kevin France

• Bob Kirshner
• Claes Fransson
• Alex Dalgarno
• Steve Lepp
• Kazik Borkowski
• John Blondin
• Rashid Sunyaev
• Claude Canizares
• Dave Burrows
• Sangwook Park
• Dan Dewey
• Eli Dwek
• Remy Indebetouw
• Julia Kamenetzky
and thanks especially to:

Sandy, Tiananmen Square, September 1987
RADIOACTIVE DEBRIS

EQUATORIAL RING

HOT FINGERS

RADIOACTIVE DEBRIS

FORWARD SHOCK WAVE

HOT GAS

REVERSE SHOCK WAVE

COOL EJECTA
Surfaces of constant Doppler shift are planar sections of the supernova debris.

\[
\frac{\Delta \lambda}{\lambda_0} = \frac{v}{c}
\]

where \( v = H_0 z \) and \( H_0 = \frac{1}{t} \).