The Remnant of SN1987A

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Topics

- Light Curves
- Reverse shock
- Hotspots
- ALMA: CO and SiO
Comments about light curves:

- Optical light from interior has faded by factor $\sim 10^{-7}$
- Luminosity of interior is dominated by Far-IR: $\sim 220 \, L_\odot$
- Far-IR is $\sim 90\%$ of energy deposited by $^{44}\text{Ti}$ decay.
- Upper limit of energy input from compact object is $\sim 30 \, L_\odot$
- Today, luminosity is dominated by near-IR and X-ray emission from shocked ring
- Optical/UV emission from ring reached a maximum at $t = 400$ days, then faded.
- Ring began to brighten again when hotspots appeared @ $t \sim 5000$ days. Now leveling off. Not as bright as initial maximum.
Reverse Shock
Surfaces of constant Doppler shift are planar sections of the supernova debris.

- Flat: $\Delta z/z < 1 \text{ month}/27 \text{ yr}$
- Thin: $\delta z/z < 10^{-3}$

Doppler Tomography

$$\Delta \lambda / \lambda_0 = v/c$$

where $v = H_0 z$ and $H_0 = 1/t$
Line emission and impact ionization at reverse shock surface

\[ \Delta \nu / \nu = v_\parallel / c \]

- \( \text{H}^* \rightarrow \text{H} + h\nu \)
- \( \text{H} + p \rightarrow 2p + e \)
- \( \text{H}_\alpha, \text{Ly}_\alpha \)
- \( \text{H} + p \rightarrow \text{H}^* + p \)
What we have learned from STIS

• Reverse shock has entered equatorial ring
• RS is expanding with radial velocity $\sim 1400$ km/s
• Can map H$\alpha$ emission from near side of internal debris, expanding with velocity $\sim 6000$ km/s
• Can’t see much H$\alpha$ from far side because of internal dust
Hotspots

[Images of hotspots from different months and years, starting from Sep. 1994 to Jun. 2014]
Optical emission from the ring began to brighten when Spot 1 appeared, at ~5000 days. It began to fade at ~8000 days.
X-ray emission continued to brighten until ~9000 days, may be leveling off now.
When spots first appeared, they were inside a diffuse ring at radii ~3 - 10% less than the ring radius. Then they began moving outward.
Distance of SN1987A

\[ D = \frac{d}{\theta}, \text{ where:} \]
\[ d = \text{line of sight diameter (from IUE light curves of narrow lines)} \]
\[ \theta = \text{angular diameter (from Hubble image)} \]

The mistake:
Hubble image (pre-hotspots) was low density ring
IUE light curves were dominated by ring of hotspots

Should use Hubble image of hotspots: reduce \( \theta \) by 5%.
a \( D \) should be increased by 5%, from 51.2 \( \pm \) 3 to 53.7 \( \pm \) 3 kpc
Structure of a “radiative” shock

Cooling timescale is a sensitive function of shock velocity: $n_0 t_{\text{cool}} \propto V_{\text{shock}}^{3.8}$.

Such “radiative shocks” are subject to violent instabilities.
• $n_0 t \sim V^{3.8}$
• $p \sim n_0 V^2$
• $V \sim [p/n_0]^{1/2}$
• $n_0 t \sim p^{1.9} n_0^{-1.9}$
• $n_0 \sim p^{0.5} t^{-0.3}$
The Velocity of shocks entering clumps is determined by driving pressure of outer SN debris across the reverse shock:

\[ p = \rho_{\text{debris}} \cdot V_{\text{debris}}^2, \text{increases fast: } p \propto t^{3.5}. \]

If shock is radiative, optical luminosity increases rapidly with time, \( L(t) \propto t^{5.25} \) to maximum value \( L_{\text{max}} \propto n^2 \).

There is a critical density, \( n_{\text{crit}} \approx 10^4 \text{ cm}^{-3} \), below which the shocks will be non-radiative. The shocked gas will radiate soft X-rays and very little optical radiation. The shocks will erase optical narrow line emission.
Conclusions

• The early (t< 3 year) light curve (IUE) of the ring was dominated by dense (n > 3 × 10^4 cm^{-3}) hotspots.

• The ring imaged by Hubble (before hotspots appeared) was dominated by less dense (n < 3 × 10^3 cm^{-3}) gas.

• The ring that IUE measured is smaller than the Hubble ring. Allowing for this increases SN1987A distance estimate by ~ 5%.

• Hotspots manifest radiative shocks entering dense clumps.

• Hotspots are fading now, as instabilities dissolve dense gas formed by radiative shocks.

• X-ray emission is dominated by non-radiative shocks in lower density gas. X-rays continued to rise as hotspots faded.

• New hotspots are appearing outside ring in SE quadrant.

• This scenario begs for 2- or 3-d hydro simulations.
Mapping of Internal Debris with ALMA
ALMA Spectra

FWHM 2150 ± 50 km/s

FWHM 2270 ± 190 km/s

Continuum = non-thermal emission from ring
Inferring properties of molecular zones from emission lines

e.g. CO 2-1, \( L_{21} = 1.05 \times 10^{32} \text{ ergs/s} \);

If optically thin, uniform density:
\[
L_{2-1} = N_{\text{CO}} f_2 A_{21} h \nu_{21}; \, \nu_{21} = 230 \text{ GHz}; \, A_{21} = 6.9 \times 10^{-7} \text{ s}^{-1}
\]

If LTE: \( f_2 = 5G(T)^{-1} \exp(-E_2/kT) \)
\[
N_{\text{CO}} = 3.3 \times 10^{53}; \, M_{\text{CO}} = 7.9 \times 10^{-3} \, M_\odot
\]

Filling factor: \( f_{\text{CO}} = V_{\text{CO}}/V_{1200} \)
\[
V_{1200} = 4\pi/3 \times [1200 \text{ km/s} \times 28 \text{ years}]^3
\]
\[
n_{\text{CO}} \approx 60 \text{ cm}^{-3}/f_{\text{CO}}
\]

SiO, \( \nu_{54} = 217 \text{ GHz} : A_{54} = 5.2 \times 10^{-4} \text{ s}^{-1} \approx 700 \, \text{A}_\text{CO} \)
Sobolev approximation

\[ L = L_{\text{thin}} \, P_{\text{esc}}(\tau_S), \text{ where } P_{\text{esc}}(\tau_S) = \frac{[1 - e^{-\tau_S}]}{\tau_S}, \]

and, for freely expanding debris,

\[ \tau_S(J, J - 1) = \frac{\lambda_0^3 t g_J A_{J, J-1} n_{J-1}}{8\pi g_{J-1}} \left( 1 - \frac{g_{J-1} n_J}{g_J n_{J-1}} \right) \]

\[ \tau_S \propto n_0/T \]
A sequence of models for line emission

4. The RADEX Code
   - Accurate in general: calculates level populations using Sobolev approximation
   - Line luminosities depend on $M_{\text{CO}}$, $f_{\text{CO}}$, $T_{\text{kinetic}}$, collision rates

\[
\text{LTE approx is OK for } J < 4
\]
Allowable CO parameter space determined from ALMA + SPIRE Observations

\[ M_{\text{CO}} > 0.01 \, M_\odot \]
\[ T_{\text{CO}} \approx 10 - 80 \, \text{K} \]
\[ f_{\text{CO}} \approx 0.05 - 1 \]
\[ L_{\text{CO}} \approx 1 - 40 \, L_\odot \]
Isotopologues

e.g. $^{13}$CO: $\nu_{21} = 220.4$ GHz, not seen!

$L_{21}(^{13}$CO)/$L_{21}(^{12}$CO) < 0.07

But $L_{21}(^{13}$CO)/$L_{21}(^{12}$CO) = $[A_{13}/A_{12}][P_{esc}(^{13}$CO)/$P_{esc}(^{12}$CO)]

$A_{13}/A_{12} = 1.09 \times 10^{-2}$

$P_{esc}(^{13}$CO) $\approx$ 1; $P_{esc}(^{12}$CO) $\approx$ 1/$\tau_S$

no $^{13}$CO implies $\tau_S < 7$, $n_{CO}/T < 3.8$
Cycle 2 Angular Resolution (Band 7, 1.5 km baseline)
ALMA Imaging
Findings from ALMA

- $M_{\text{CO}} > 0.01 M_\odot$ – at least 10 times more than seen at 18 months
- $T_{\text{CO}} \approx 10 - 80$ K
- CO J = 3-2 line is brighter than J = 2-1 by factor 3.4
- Can map CO and SiO at resolution $\sim 0.03 \arcsec$
\[\tau_{S}(J, J - 1) = \frac{\lambda_0^3 t g_J A_{J, J-1} n_{J-1}}{8\pi g_{J-1}} \left(1 - \frac{g_{J-1} n_J}{g_J n_{J-1}}\right)\]

\[\tau_{21} = 0.13^3 * 30*3.11e7*5*6.9e-7*3n0*/\exp(-E1/kT)[1-\exp(-E2+E1)/kT]/[8*3\pi G(T)]\]

\[E2-E1/k = (5-3)E0k = h*2.30e9/k = 11/T\]

\[1.3^3*3*3.11*5*6.9*3 e(-3+1+7-7) = 102.47\]