Supernova 1987A at 27 Years

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TOPICS

• SN1987A today (27 years)
• Cold gas & dust – a little ancient history
• ALMA Observations and interpretation
• The future
The gift of astronomical technology

<table>
<thead>
<tr>
<th></th>
<th>1987</th>
<th>2000</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>ATCA</td>
<td></td>
<td>ALMA</td>
</tr>
<tr>
<td>Far IR</td>
<td>KAO</td>
<td>Spitzer</td>
<td>Herschel</td>
</tr>
<tr>
<td>Optical/NIR</td>
<td>Magellan</td>
<td>VLT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gemini-S</td>
<td>HST</td>
<td></td>
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<tr>
<td>UV</td>
<td>IUE</td>
<td></td>
<td>HST</td>
</tr>
<tr>
<td>X-rays</td>
<td>Ginga</td>
<td>ROSAT</td>
<td>Chandra</td>
</tr>
<tr>
<td></td>
<td>Mir-Kvant</td>
<td></td>
<td>XMM</td>
</tr>
<tr>
<td>γ-rays</td>
<td>SMM</td>
<td></td>
<td>Compton</td>
</tr>
</tbody>
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Supernova 1987A • December 6, 2006
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)
Three views of the supernova debris and its shock interaction with the circumstellar ring
SN 1987A Debris Light Curve

$^{56}\text{Co} (0.07 \, M_\odot)$

Magnitude

X-rays

$^{57}\text{Co}$

$^{44}\text{Ti}$

Years after explosion

B

R

Source?
Crash!  Impact of blast wave with ring
Shocked, X-Rays

H/He Envelope
Asymmetry of Debris
Hammer et al. 2008: Neutrino – driven 3-d explosion simulation

Large-scale instability- SASI

But: initial conditions?? Violent convection mixes shells before explosion
Dust and molecule formation: $t = 1 - 2$ years

Dust continuum:
$T \sim 500$ K, $M_d \sim 10^{-4} M_\odot$

SiO $\Delta \nu = 1$

CO $\Delta \nu = 1$
$M_{CO} \sim 10^{-3} M_\odot$
$T \sim 2500 - 1500$ K
Line Profile Changes due to Internal Dust Formation

Apparent blue-shift of line centroid due to absorption of emission from far side.

\[ \Delta \lambda / \lambda_0 = V_l / c \]
\[ V_l = z / t \]
Dust Continuum: New Results from Herschel

Inferred dust mass $M_d = 0.4 - 0.7 \, M_\odot$ !!!
ALMA Cycle 0 Observations

April 2012: Band 3 (2.7 – 3 mm) 14 – 18 antennas

August 2012: Band 6 (1.3 – 1.4 mm) 14 – 23 antennas

Maximum Baseline: 0.4 km
Continuum Images & SED
ALMA Spectra

- **FWHM of 2150 km/s ± 50 km/s**
- **FWHM of 2270 km/s ± 190 km/s**

- **Continuum** = non-thermal emission from ring CO 6-5 7-6
Emission Line Images
A little physics ...
Modeling of CO Emission

• Assume emitting CO is found in clumps of C/O gas all having same density and temperature

• Line luminosities depend on 3 parameters:
  – Temperature of gas
  – Mass of CO
  – Net Volume, $V_{CO}$, of CO clumps

  • Linewidth of CO implies emitting clumps confined within sphere expanding at $v_{exp} = 2000$ km/s:
    • $V_{exp} = (4\pi/3) \ (v_{exp} \ t)^3$
    • Define filling factor $f_{CO} = V_{CO}/V_{exp}$
A sequence of models for line emission

1. LTE, optically thin

\[ L_{\text{thin}}(J, J - 1) = A_{J,J-1} h \nu_{J,J-1} \left[ \frac{M_{\text{CO}}}{28m_H} \right] \left[ \frac{(2J + 1)}{G(T)} \right] \exp(-E_J/kT) \]

- Depends only on \( M_{\text{CO}} \) and \( T_{\text{CO}} \)
- Gives lower limit to emitting mass: \( M_{\text{CO}} > 0.01 M_\odot \)
- Implies \( L_{2-1}/L_{1-0} \approx 16 \) – in conflict with observed ratio
Doppler Tomography of Interior

- Surfaces of constant Doppler shift are planar sections of the supernova debris
- Fractional thickness \( \sim a_s/V_{\text{exp}} \sim 10^{-4} \)

\[
\Delta \lambda / \lambda_o = v/c
\]

where \( v = z/t \)

\( A_{\text{CO}} \rightarrow \text{To observer} \)
A sequence of models for line emission

2. Optically thick

\[ I_{thick}(\nu) = B_\nu(T)A_{CO}(z) \]

\[ L_{thick}(\nu_J, J-1) = 4\pi \int I_{thick}(\nu) d\nu \quad d\nu = \left[ \frac{\nu_0}{ct} \right] dz \]

\[ L_{thick}(\nu_J, J-1) = \left[ \frac{4\pi\nu_J, J-1}{ct} \right] B_\nu(T) \int A_{CO}(z)dz \]

- Depends on \( V_{CO} \) and \( T_{CO} \), independent of mass and density of emitting regions
- Gives lower limit to volume filling factor: \( f_{CO} > 0.05 \)
- Implies \( L_{2-1}/L_{1-0} \approx 8 \)
  - in agreement with observed ratio \( 7.9 \pm 2.0 \)
This same approximation implies \( L_{3-2}/L_{2-1} \approx 3 \)
A sequence of models for line emission

3. Sobolev approximation*

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

and, for freely expanding debris,

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

*valid for hypersonic expansion, whether or not LTE, and makes a smooth transition between the optically thin and thick limits.
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

![Graph showing luminosity vs. upper J]

LTE approx is OK for $J < 4$
Allowable CO parameter space determined from ALMA + SPIRE Observations

\[
M_{\text{CO}} > 0.01 \, M_\odot
\]

\[
T_{\text{CO}} \approx 10 - 80 \, \text{K}
\]

\[
f_{\text{CO}} \approx 0.05 - 1
\]

\[
L_{\text{CO}} \approx 1 - 40 \, L_\odot
\]
Conclusions

• Optically thick CO 2-1 and 1-0 rotational transitions were detected with ALMA
• CO emission comes from center of debris
• Temperature $\sim 40$ K (20 - 80 K)
• CO mass $\geq 0.01 \, M_\odot$

$\gg$ vibrationally-detected CO was $10^{-3} \, M_\odot$

$\Rightarrow$ most CO formation occurred after 2 years.

• Volume filling factor (of 2000 km s$^{-1}$ sphere)
  \[ f_{\text{CO}} > 0.01 \]
• CO luminosity small compared to dust luminosity
• Also have seen SiO, not necessarily from same chemical zone
• Future Work...
Unfinished Agenda – modeling molecule formation

- \( O + e \rightarrow O^- + h\nu \)
- \( C + O^- \rightarrow CO + e \), or ?:
- \( O + \text{carbon grain} \rightarrow CO + \text{grain} \)

and destruction by X-rays and \( \gamma \)-rays

\( CO + \text{fast } e \rightarrow C + O \), or, if He present,
\( CO + \text{He}^+ \rightarrow C^+ + O + \text{He} \)
What’s Next?

• Up to now, our analysis has been based only on total line luminosities

• Cycle 1 Observations: Higher angular resolution and sensitivity
  – Good chance of seeing large scale anisotropy

• CO J=3-2 prediction for Band 7: 65 mJy peak

• Cycle 2: image the line profile \(\rightarrow\) 3D Doppler tomography of interior: Higher angular resolution and sensitivity
  – Angular resolution \(\sim 0.15''\)
  – Spatial distribution of SiO probably different from CO
• No reason to expect line profile to be a smooth Gaussian
• Already see hint of lumpiness
• Doppler tomography was used with HST & VLT, but ALMA Bands 6 and 7 (CO 2-1, 3-2) will give higher angular resolution and will not be obscured by dust
• Extent of mixing? How is C/O region producing CO different from Si/O region producing SiO emission?

\[ \Delta \lambda / \lambda_o = v/c \]
where \( v = z/t \)
Cycle 2
≥ 45 antennas, Baseline > 1.5 km
Cycle 2 Angular Resolution (Band 7, 1.5 km baseline)
Band 6: can get CO 2-1 and SiO 5-4 in one shot. Angular resolution 0.15” for baseline 1.5 km.

Band 7: CO 3-2 and SiO 8-7 overlap

Band 9: best bet is SiO 15-14 (651 GHz). Angular resolution ~ 0.07”
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