CIRCUMSTELLAR GAS AROUND SN 1987A

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(Talk at AlbaNova, August 12, 2011)
THE SN 1987A ENVIRONMENT

After and before explosion (AAO)

SN 1987A + Honeycomb Nebula (ESO)
THE SN 1987A ENVIRONMENT

SN 1987A + Honeycomb Nebula (ESO)  SN 1987A in 1999 (HST)

Thursday, August 18, 2011
FIRST EVIDENCE OF CIRCUMSTELLAR GAS

Radio

Early 843 MHz lightcurve (Ball et al. 1995)

IUE Observations (Sonneborn et al. 1997)
THE INNER RING

- Densities range between \((0.6 - 3.3) \times 10^4\) cm\(^{-3}\).
- Burst: 500full1 (Ensman & Burrows 1992)
- Abundances: He/H = 0.25, N/C = 5.0, N/O = 1.1, \((C+N+O) = (He + H + Z) = 0.30\) solar
- Radius: \(6.3 \times 10^{17}\) cm and Ionized mass: 0.045 M\(_\odot\)
- NV \(\lambda 1240\) is the only resonance line – requires further constraints to be successfully modeled.

Shock breakout (Ensman & Burrows 1992)

Sweeping of the light echo paraboloid across the ring system.

Geometry of the rings (Lundqvist 2007)
No surprise that 500full1 and 14E1 by Blinnikov et al. (2000) give very similar results. Is the burst now fully constrained?

Same as in Lundqvist & Fransson (1996), but with updated atomic data and with new burst.

- Solid lines: Blinnikov et al. (2000) 14E1 burst.
- Densities range between (0.6 – 3.2)x10^4 cm^{-3}.
- Abundances: He/H = 0.25, N/C = 4.5, N/O = 1, (C+N+O) = (He + H +Z) = 0.29 solar
- Radius: 6.2 x 10^{17} cm.
- N V λ1240 not so well modeled
IF we believe the burst is fixed we can use the ring to test atomic data:

- Dashed: Old data for $\text{N VI} \rightarrow \text{N V}$ dielectronic recombination. (Used in LF96.)
- Solid: Data from Nahar & Pradhan (1997). 50% lower at $10^5 \text{ K}$.
- Could also signal that we have left out a low-density component
THE INNER RING AT LATER EPOCHS

Light curves for many more lines (Mattila et al. 2010)

• Densities: $3 \times 10^4$ cm$^{-3}$, $3 \times 10^3$ cm$^{-3}$ and $1 \times 10^3$ cm$^{-3}$.
• Abundances: He/H = 0.25, N/C = 4.5, N/O = 1, (C+N+O) = (He + H + Z) = 0.29 solar
• Radius: $6.2 \times 10^{17}$ cm.
• N V λ1240 not so well modeled
THE INNER RING AT LATER EPOCHS

Light curves for many more lines (Mattila et al. 2010)
THE INNER RING AT LATER EPOCHS

- Abundances: $\text{He}/H = 0.17 \pm 0.06$ and $\text{N}/O = 1.5 \pm 0.7$.
- With $\text{N}/C = 5$ from Lundqvist & Fransson (1996)
  \[
  (\text{C}+\text{N}+\text{O}) = (\text{He} + \text{H} + \text{Z}) = 0.33 \text{ solar (Anders & Grevesse 1989)}
  \]
  \[
  (\text{C}+\text{N}+\text{O}) = (\text{He} + \text{H} + \text{Z}) = 0.60 \text{ solar (Grevesse et al. 2007)}
  \]
  \[
  (\text{C}+\text{N}+\text{O}) = (\text{He} + \text{H} + \text{Z}) = 1.6 \text{ LMC (Russell & Dopita 1992)}
  \]
- Fe abundance is $\sim 0.2$ solar (Anders & Grevesse 1989) or $\sim 0.3$ solar (Grevesse et al. 2007).
- In general we obtain higher metal abundances than X-ray findings (e.g. Zhekov et al. 2009)
- Total ionized mass is $\sim 0.058 \text{ M}_\odot$.
Narrow-line light curves (Mattila et al. 2010)

- A 4th density $0.018 \, M_\odot$ component ($10^2 \, \text{cm}^{-3}$) added to explain late emission.

Why a $10^2 \, \text{cm}^{-3}$ component?
INSIDE THE INNER RING

- Photoevaporation of the cool shell
- H II-region has a density of around $10^2$ cm$^{-3}$. Helium neutral (Lundqvist 1999).
- BSG wind: $< 10^{-8}$ M$_o$ yr$^{-1}$
- Broad region of H II-region (roughly half of ring radius)

Radio upturn after ~1000 days

(Talk on radio by Ng!)
INSIDE THE INNER RING

Lundqvist (1999)

FUSE observations around O VI $\lambda$1032 (Sonneborn et al. in prep.)
THE INNER RING AT PRESENT EPOCHS

Narrow-line light curves (Mattila et al. 2010)

- One more source needed at late times.

The ejecta/ring interaction!

(Mattila et al. 2010)
WHEN THE SN EJECTA REACHED THE INNER RING

Evolution of ring spots until 2007 (SAINTS collaboration)
(First spot seen in 1997.)

Michael et al. (2000)

(Talk on reverse shock by France!)

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WHEN THE SN EJECTA REACHED THE INNER RING

(Talks on X-rays by Park & Larsson)

Allen et al. (2008)
EJECTA/RING INTERACTION

[O III] from the northern part of the ring (Gröningsson et al. 2008a)

Evolution and diagnostic (day 5704) of the narrow velocity component from the northern part of the ring (Gröningsson et al. 2008ab)
EJECTA/RING INTERACTION

Evolution and diagnostic (day 5704) of the narrow velocity component from the northern part of the ring (Gröningsson et al. 2008ab)
EJECTA/RING INTERACTION

Ratio map \([\text{O III}] \ (2006) / [\text{O III}] \ (2003)\) (SAINTS)

Borkowski et al. (1997)
AWAY FROM THE INNER RING

Structure of the reverse shock
(Michael et al. 2003)

(Talk by France!)
THE RING SYSTEM

Crotts & Heathcote (2000)

Maran et al. (2000)

VLT Observations (FORS + UVES)
(Tziamtzis et al. 2011)
THE OUTER RINGS

Simple model for the geometry of the ring system:
- Rings intrinsically circular
- Motion close to ballistic ($a = -21.5 \text{ km/s}$, $b = 22.3 \text{ km/s}$, $c = 24.3 \text{ km/s}$, $d = 21.1 \text{ km/s}$).
- Rings have their normal vector in x-z plane.
- Should intersect M1 and M2 (from Maran et al. 2000).
- Assume a distance of 50 kpc.

Result:
- Inclination angles of NOR, ER and SOR are: $45^\circ$, $43^\circ$ and $38^\circ$, respectively.
- Both NOR and SOR are shifted westward with respect to the SN.
- Distances to M1 and M2 are $1.65 \times 10^{18} \text{ cm}$ and $2.05 \times 10^{18} \text{ cm}$. (Not both $2.0 \times 10^{18} \text{ cm}$ as in Maran et al. 2000).
THE OUTER RINGS

Southern outer ring spectra in 2002
(Tziamtzis et al. 2011)
### THE OUTER RINGS

**Table 8. Compilation of plasma diagnostics for the outer rings of SN1987A.**

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Corrected epoch $^a$</th>
<th>Ring</th>
<th>$N_e$ (cm$^{-3}$)</th>
<th>$T$ (K)</th>
<th>Diagnostic</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>2877</td>
<td>2192</td>
<td>SOR</td>
<td>$&lt;1.3 \times 10^{18}$</td>
<td></td>
<td></td>
<td>[O II]</td>
</tr>
<tr>
<td>2877</td>
<td>2217</td>
<td>NOR</td>
<td>$&lt;1.3 \times 10^{20}$</td>
<td></td>
<td></td>
<td>[O II]</td>
</tr>
<tr>
<td>4282</td>
<td>3099</td>
<td>NOR</td>
<td>$&lt;2.2 \times 10^{20}$</td>
<td></td>
<td></td>
<td>[S II]</td>
</tr>
<tr>
<td>4282</td>
<td>4022</td>
<td>SOR</td>
<td>$&lt;1.6 \times 10^{20}$</td>
<td></td>
<td></td>
<td>[S II]</td>
</tr>
<tr>
<td>5702–5705</td>
<td>4902–4905</td>
<td>SOR</td>
<td>$&lt;1.0 \times 10^{20}$</td>
<td></td>
<td></td>
<td>[O II]</td>
</tr>
<tr>
<td>5702–5705</td>
<td>4902–4905</td>
<td>SOR</td>
<td></td>
<td>$(1.00–1.10) \times 10^{5}$</td>
<td>[N II]</td>
<td>This paper</td>
</tr>
<tr>
<td>5702–5705</td>
<td>4902–4905</td>
<td>SOR</td>
<td></td>
<td>$(1.95–2.00) \times 10^{6}$</td>
<td>[N II]</td>
<td>This paper</td>
</tr>
<tr>
<td>5702–5705</td>
<td>4934–4937</td>
<td>NOR</td>
<td></td>
<td>$\sim 1.2 \times 10^{6}$</td>
<td>[O III]</td>
<td>This paper</td>
</tr>
<tr>
<td>5702–5705</td>
<td>4934–4937</td>
<td>NOR</td>
<td></td>
<td>$\sim 2.7 \times 10^{6}$</td>
<td>[O III]</td>
<td>This paper</td>
</tr>
<tr>
<td>5791</td>
<td>4991</td>
<td>SOR</td>
<td>$&lt;3.3 \times 10^{3}$</td>
<td></td>
<td></td>
<td>[S II]</td>
</tr>
<tr>
<td>5791</td>
<td>4991</td>
<td>SOR</td>
<td></td>
<td>$(1.3–1.4) \times 10^{4}$</td>
<td>[N II]</td>
<td>This paper</td>
</tr>
<tr>
<td>5791</td>
<td>4991</td>
<td>SOR</td>
<td></td>
<td>$\sim 2.5 \times 10^{6}$</td>
<td>[O III]</td>
<td>This paper</td>
</tr>
<tr>
<td>7944–8021</td>
<td>7144–7221</td>
<td>SOR</td>
<td>$&lt;2.3 \times 10^{3}$</td>
<td></td>
<td></td>
<td>[O II]</td>
</tr>
<tr>
<td>7944–8021</td>
<td>7144–7221</td>
<td>SOR</td>
<td></td>
<td>$&lt;3.0 \times 10^{5}$</td>
<td>[S II]</td>
<td>This paper</td>
</tr>
<tr>
<td>7944–8021</td>
<td>7144–7221</td>
<td>SOR</td>
<td></td>
<td>$(1.15–1.25) \times 10^{6}$</td>
<td>[N II]</td>
<td>This paper</td>
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<tr>
<td>7944–8021</td>
<td>7176–7253</td>
<td>NOR</td>
<td></td>
<td>$\sim 1.2 \times 10^{6}$</td>
<td>[N II]</td>
<td>This paper</td>
</tr>
</tbody>
</table>

*Notes.* $^{(a)}$ In days. Corrected for light-travel time. $^{(b)}$ Allowing for a higher temperature than Panagia et al. (1996).

*(Tziamtzis et al. 2011)*

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THE OUTER RINGS

Some findings:

- From H-alpha decay; density as high as $5 \times 10^3$ cm$^{-3}$. From forbidden lines $< 3 \times 10^3$ cm$^{-3}$.
- Area 4 (T1) is redshifted by 6 km/s compared to the model.
- Density and temperatures are similar for the two outer rings.
- When the SN shock reaches the outer rings, the cloud shock may not be radiative as for the inner ring.
- The densities are somewhat higher than that of the inner ring, assuming simple “ballistic” expansion.

HST photometry
(Tziamtzis et al. 2011)
THE OVERALL STRUCTURE

N V $\lambda$1240 scattering.
Could be an important probe of the geometry.
Further simulations needed!

*Figure 10. Mass enhancements in the ejecta flow, corresponding to merger models for SN1987A (left-hand panel, Model 1 from section 3.1 with $\alpha = 0.33$ and $\beta = 0.817$) and Sheridan 25 (right-hand panel; Model 2 from section 3.2 with $\alpha = 0.35$ and $\beta = 0.665$). The solid curves give the locations that contain 50% of the mass ejected at a particular solid angle at the time as indicated (in code $t$). ($M_1 + M_2 = 20 \, M_\odot$, $P \sim 10$ yr).*

*Morris & Podsiadlo\l{}ski (2005)*
CONGRATULATIONS!