15 years of SN 1996al & CSM around masssive stars

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The spectacular evolution of Supernova 1996al over 15 yr: a low-energy explosion of a stripped massive star in a highly structured environment

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Introduction: Massive stars may show pre-explosion activity & weak explosions

Close CSM —> could magnifies low energy explosions

SN 2009ip - Pastorello+ 2013

LSQ13zm - Tartaglia+ 2016
Why massive stars should end-up with dim explosions?

SN 1996al is one of these; let’s see why!
SN 1996al progenitor star has been recovered!

$L_{\text{H\alpha}}$ (precursor) $\sim 37.28$ dex

rate ionizing radiation $\sim 10^{49}$ photons s$^{-1}$

star with bol lum log $L/L\odot > 5.4$ & $R \sim 10R\odot$

$M_{\text{ZAMS}} \sim 25 M\odot$ -> lost most of external H mantle

Caldwell+ 1991

NGC 7689
SN 1996al: a linear supernova

$\text{SN } 1996\text{al: a linear supernova}$

$\log_{10} L_{\text{erg/s}}$

$\text{days from explosion}$

$\text{98S}$

$\text{87A}$

$^{56}\text{Ni} + ^{56}\text{Co}$
No broad P-Cygni absorptions!

photosphere forms in a clumpy CDS where CSM and ejecta collide!
Light curve modelled with a weak explosion + interaction

\[ \text{Output:} \quad (\text{VU radiation hydrodynamic c.}) \]

\[ M_{\text{ej}} = 1.15 \, M_\odot \quad (0.15 \, \text{H} + 1 \, \text{He}) \]

Input:
\[ (M_{\text{ZAMS}} \approx 25 \, M_\odot; \quad R = 10R_\odot) \]
\[ M_{\text{He-core}} \approx 8.3 \, M_\odot; \quad M_{\text{env}} \approx 0.3 \, M_\odot \]

\[ E_K = 1.6 \times 10^{50} \, \text{erg} \]

interacts with
\[ M_{\text{CSM}} = 0.13 \, M_\odot \quad (r < 3 \times 10^{16} \, \text{cm}) \]

thickness eq. disk \approx 23^\circ

layers below He fell back >
collapsing core \rightarrow 7-8 \, M_\odot

Black Hole!

anisotropic: equatorial disk-like +
clumpy, more symmetric CS

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Spectroscopic evolution over 15 years!

early on $\text{H}_\alpha$ profile more symmetric and with some Thompson scattering

$\text{H}_\alpha$ profile $> 100^\circ$ supports disk-like CS
Early on HeI already shows some asymmetry! which suggests that emitting surface has an oblate shape.

with time the degree of asymmetry (in He lines) tends to decrease and

HeI 5876Å -> NaID
HeI 5876Å photons coming from deep inside -> NaID

This tells that HeI 5876Å photons are emitted symmetrically deep inside the ejecta —> explosion is symmetric!!!
all in a cartoon:

inner radius equatorial disk $\sim 3 \times 10^{15}$ cm
external limit $> 5 \times 10^{17}$ cm (0.15pc; H$\alpha$ visible for 15 years)
($M_{\text{CSM}}>0.13 M_{\odot}$)
(thickness eq. disk~23°)
Equatorial disks are indeed seen around massive stars!

Gvaramadze+ 2015

Table 7. Blue supergiants and cLBVs with hourglass-like circumstellar nebulae.

<table>
<thead>
<tr>
<th></th>
<th>Sk−69°202</th>
<th>Sher 25</th>
<th>HD 168625</th>
<th>[SBW2007] 1</th>
<th>MN18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral type</td>
<td>B3 I(1)</td>
<td>B1.5 Iab(2)</td>
<td>B6 Iap(3)</td>
<td>B1 Iab(4)</td>
<td>B1 Ia</td>
</tr>
<tr>
<td>log (L/L⊙)</td>
<td>≈5(5)</td>
<td>5.8(6)</td>
<td>5.0–5.4(7)</td>
<td>4.7(8)</td>
<td>5.4</td>
</tr>
<tr>
<td>Teff (kK)</td>
<td>16(5)</td>
<td>22(6)</td>
<td>12–15(7)</td>
<td>21(8)</td>
<td>21</td>
</tr>
<tr>
<td>Ṁ(10⁻⁷ M⊙ yr⁻¹)</td>
<td>1.5–3(9, 10)</td>
<td>20(6)</td>
<td>11(7)</td>
<td>2–4(8)</td>
<td>4.2–6.8</td>
</tr>
<tr>
<td>r (pc)</td>
<td>0.2(11)</td>
<td>0.2(12)</td>
<td>0.2(7)</td>
<td>0.2(13)</td>
<td>0.3</td>
</tr>
<tr>
<td>n_e([S II]) (cm⁻³)</td>
<td>~10 000(14, a)</td>
<td>500–1800(15)</td>
<td>≈1000(7)</td>
<td>≈500(13)</td>
<td>≈600</td>
</tr>
<tr>
<td>M_{ring}</td>
<td>0.06(16)</td>
<td>0.1(15)</td>
<td>0.5(7)</td>
<td>0.5–1.0(8)</td>
<td>1</td>
</tr>
<tr>
<td>v sin i (km s⁻¹)</td>
<td>–</td>
<td>53</td>
<td>44</td>
<td>34</td>
<td>90</td>
</tr>
<tr>
<td>i (°)</td>
<td>43(17)</td>
<td>65(12)</td>
<td>60(18)</td>
<td>50(13)</td>
<td>60</td>
</tr>
<tr>
<td>v_{exp} (km s⁻¹)</td>
<td>10(19)</td>
<td>30(15)</td>
<td>20(20)</td>
<td>19(13)</td>
<td>8</td>
</tr>
<tr>
<td>t_kin (10⁴ yr)</td>
<td>2</td>
<td>0.7</td>
<td>1</td>
<td>1</td>
<td>3.7</td>
</tr>
<tr>
<td>Ṁ_{kin}/Ṁ</td>
<td>10–20</td>
<td>7</td>
<td>45</td>
<td>250</td>
<td>40–60</td>
</tr>
<tr>
<td>log (N/H)+12</td>
<td>8.44(16)</td>
<td>8.91(6)</td>
<td>8.42(7)</td>
<td>7.51(13)</td>
<td>8.21</td>
</tr>
</tbody>
</table>

References: (1) Walborn et al. (1989); (2) Moffat (1983); (3) Walborn & Fitzpatrick (2000); (4) Taylor et al. (2014); (5) Arnett et al. (1989); (6) Hendry et al. (2008); (7) Nota et al. (1996); (8) Smith et al. (2013); (9) Blondin & Lundqvist (1993); (10) Martin & Arnett (1995); (11) Panagia et al. (1991); (12) Brandner et al. (1997a); (13) Smith et al. (2007); (14) Plait et al. (1995); (15) Brandner et al. (1997b); (16) Mattig et al. (2010); (17) Jakobsen et al. (1991); (18) O’Hara et al. (2003); (19) Crotts & Huchra (1981); (20) Hutsemekers et al. (1981).

*aBased on the fading of the [S II] λ6717 emission line.
re-brighting due to late fall-back, interaction?
No Oxygen in late time spectra: fall back confirmed!
Not the only one!

SN 1996al

Benetti+ 1999

SN 1994aj

Benetti+ 1998

SN 1996L
Summary

SN 1996al: low energy explosion of a massive star ($M_{ZAMS}$~25 $M_\odot$; 7-8$M_\odot$ BH) sustained by ejecta-asym CSM interaction

$M_{CSM} > 0.15 M_\odot$; with a ring-like ($r_{\text{ext}} \sim 0.15$ pc; $r_{\text{inner}} \sim 3 \times 10^{15}$ cm) plus more symmetrically distributed clumps.

Growing indication that massive stars have strong mass loss episodes just before explosion, and sometimes have asymmetric CSM.

We have derived the CSM shape/properties just analysing the SN spectrophotometric evolution of the supernova!

Supernovae can be powerful tools to probe the local CSM -> gives informations on the progenitor star evolution just before explosion!

Crete 10 June 2016
Thanks!