SN 2001em:
the Case for an Off-Axis Relativistic Jet

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Outline of the Talk:

- SN 2001em: Type Ic or II n?
- Interpretations of the late time radio emission:
  - Interaction of SN shell with circumstellar medium
  - A relativistic jet pointing away from us, at $t \sim t_{NR}$
- $L_x(10^3 \text{ d}) \sim 10^{41} \text{ erg/s} \Rightarrow E(\beta \sim 1) \geq 10^{51} \text{ erg}$
- How to verify mildly relativistic expansion now
- Implications, if it is an off-axis relativistic jet
  - “Orphan afterglows”
  - Core collapse SNe
- Conclusions
SN 2001em: Type Ic, $D \approx 80$ Mpc

Host galaxy: UGC 11794, $z = 0.019493$ (Papenkova et al. 2001)

Early Spectrum: Type Ic

Late Spectrum: Type II In

(Soderberg et al. 2004)
SN 2001em: Late Time Radio Emission

$F_\nu \propto t^{1.9 \pm 0.4} \nu^{-0.36 \pm 0.16}$

SN Type Ic

SN Type IIn

SN Type Ic

SN Type IIa

SN 1994I

SN 1998ew

SN 2001em
Interpreting the Radio Emission

1. Interaction of the SN shell with the circumstellar medium

- Typically: Optically thick during the rising stage & optically thin during the decay

![Graph showing radio emission data for SN 1993J with wavelengths 1.3 cm, 2.1 cm, 3.6 cm, 6.3 cm, and 21 cm over time.

\[ \lambda = \begin{array}{c} 1.3 \text{ cm} \\ 2.1 \text{ cm} \\ 3.6 \text{ cm} \\ 6.3 \text{ cm} \\ 21 \text{ cm} \end{array} \]
SN 1987A (Type IIp; in LMC, $D \approx 50$ kpc)

$v = 843$ MHz

(Ball et al. 2001)

- Sometimes there is a rising flux + optically thin spectrum (probably due to a density bump)
2. An Off-Axis Relativistic Jet:

- Naturally reproduces the observed spectral & temporal indexes

\[
\theta_{\text{obs}} \quad \theta_0
\]

\[
L_B \quad F_V
\]

- dashed: point source
- solid: uniform jet
- numerical simulation

(Granot et al. 2002)
The X-ray Luminosity at $\sim 10^3$ days

- $L_X(950 \text{ d}) \sim 10^{41} \text{ erg/s}$ (Pooley & Lewin 2004)
- $L_X \sim \varepsilon(E/t) \sim 10^{41} (\varepsilon/0.01)(E_{51}/t_8) \text{ erg/s}$
- $\varepsilon/0.01 = (f_{\text{int}}/0.5)(\varepsilon_e/0.3)(\varepsilon_{\text{rad}}/0.33)(f_X/0.2) \lesssim 1$
- $\Rightarrow E \gtrsim 10^{51} \text{ erg}$ (energy in shocked external medium)
- $E_{\text{tot}}/E = \min[1,M(R)/M(R_{\text{dec}})]$, $E_{\text{tot}}(t\ll t_{\text{dec}}) \gg 10^{51} \text{ erg}$
- $\Rightarrow t_{\text{dec}} \lesssim 10^3 \text{ days} \Rightarrow \beta_0 \gtrsim 0.5(E_{51}/A_*)^{1/3}$
- $A_* \gg 1 \& \beta_0 \ll 1 \Rightarrow n = 4 \cdot 10^8 (E_{51}/\Delta_1)(\beta_0/0.01)^{-5} \text{ cm}^{-3}$
  $\Rightarrow$ optically thick spectrum X
- $\Rightarrow E(\beta \sim 1) \gtrsim 10^{51} \text{ erg}$
SN 2001em

(Kouveliotou et al. 2004)
Summary:

- **Currently**: external shock is mildly relativistic
  \[ L_x(10^3 \text{ d}) \Rightarrow \Gamma \beta (10^3 \text{ d}) \geq 1 \] (rather robust)

- It is difficult to infer the initial Lorentz factor \( \Gamma_0 \) or degree of collimation (jet opening angle \( \theta_0 \))

- We expect \( \theta_0 \geq 1/\Gamma_0 \) & \( \theta_j \geq 1/\Gamma \Rightarrow \text{now} \ \theta_j \geq 1 \)

- \( F_\nu \propto t^{1.9 \pm 0.4} \) requires \( \Gamma_0 \geq 2-3 \) (less robust)
How to verify if the radio emission is from mildly relativistic material

The angular size:

- For mildly relativistic expansion:
  \[ \theta_{NR} \sim c t_{NR}/D_A \sim 2.4(t_{NR}/3\text{ yr}) \text{ mas} \]
  (easily resolvable with VLBI)

- For a SN shell with velocity \( \sim 0.01c \), the angular size is \( \sim 100 \) times smaller
  (at best, marginally resolvable with VLBI)
Implication If it is a Relativistic Jet

- The radio emission requires initial L.F. $\Gamma_0 \gtrsim 2-3$
- This would provide an estimate for the fraction of SNe Ib/c that produce relativistic jets, $f_{RJ}$

Berger et al. (2003) observed 33 nearby SNe Ib/c in the radio:...
Soderberg et al. (2004) used a sample of 15 nearby Sne Ib/c With radio observation at $t > 100$ days (8 from Berger et al.)

$0.002 < \epsilon_B < 0.25$

$E_{51} = 1$

$\epsilon_e = 0.1$

$p = 2$
\[ \Rightarrow f_{RJ} \sim 1/15 \sim 7\% \quad \text{(for} \; \Gamma_0 \geq 2) \]

with a large uncertainty

- On the other hand, a GRB requires \( \Gamma_0 \geq 100 \)

- The fraction of SNe Ib/c that produce GRBs:
  - Frail et al. (2001): \( \langle f_b^{-1} \rangle \sim 500, f_{GRB} \sim 4 \times 10^{-3} \)
  - Perna et al. (2003): USJ model, \( f_{GRB} \sim 8 \times 10^{-6} \)
  - Guetta et al. (2003): (uniform jet) \[ \langle f_b^{-1} \rangle = 75 \pm 25 \; , \; f_{GRB} = (5.8 \pm 1.8) \times 10^{-4} \]

- This suggests \( f_{RJ}/f_{GRB} \sim 100 \)
More Speculative Implications:

- It is natural to expect a continuous distribution
  \( P(\Gamma_0) = K \Gamma_0^{-\eta}, \Gamma_{\text{min}} < \Gamma_0 < \Gamma_{\text{max}}, \Gamma_{\text{min}} \sim 1, \Gamma_{\text{max}} > 100 \)
  \[ K = f_{\text{RJ}}(\eta-1)(\Gamma_{\text{min}})^{1-\eta} \sim f_{\text{RJ}} \]

- \( f_{\text{RJ}} / f_{\text{GRB}} \sim 100 \Rightarrow \eta \sim 2 \)

- \( \Gamma_0 \geq 2-3 \Rightarrow \text{radio transient (} \times 100 \text{)} \)

- \( \Gamma_0 \geq 5-10 \Rightarrow \text{optical transient (} \times 10-20 \text{)} \)

- \( \Gamma_0 \geq 10-20 \Rightarrow \text{X-ray transient (} \times 5 \text{)} \)

- \( \Gamma_0 \geq 100 \Rightarrow \text{GRB (unchanged)} \)
Implications for Core Collapse SNe:

- $P(\Gamma_0)$ probably extends to Newtonian jets
- Totani (2003) inferred a jet with $v = 0.23c$ in nearby ($D=7.3$ Mpc) Type Ic SN 2002ap
- If indeed $f_{RJ} \sim 7\%$, this suggests that in most/all SNe Ib/c, and perhaps other core collapse SNe, the explosion is triggered by bipolar jets
Conclusions:

- The radio emission in SN 2001em is atypical for a SN, but is natural for an off-axis relativistic jet.
- $L_X\chi$ requires mildly relativistic expansion: $\Gamma\beta \gtrsim 1$.
- The existence of (mildly) relativistic ejecta can be clearly established or ruled out by VLBI obs.
- A rel. jet would have interesting implications:
  - A few % of SNe Ib/c produce rel. jets ($\Gamma_0 \gtrsim 2$).
  - $\sim 100$ ($\sim 15$) [$\sim 5$] times more radio (optical) [X-ray] transient compared to orphan AGs.
  - A large fraction of SNe Ib/c (maybe also other core collapse SNe) might be triggered by bipolar jets.