The role of jets in exploding supernovae and shaping their remnants

Noam Soker

• Dictionary translation of my name from Hebrew to English (real!):
  Noam = Pleasantness
  Soker = Review
A short summary

JETS

See review posted to astro-ph in May 2016:
The galaxy cluster MS 0735.6+7421: An X-ray image (red), and the radio image (blue) added in the right panel (From Brian McNamara and collaborators). The edge-to-edge linear scale is about one million light year.
Galaxy Cluster MS 0735.6+7421

CXO • HST • VLA

Chandra X-Ray Observatory

Visible
Hubble Space Telescope

Radio
Very Large Array

NASA, ESA, CXC/NRAO/STScI, B. McNamara (University of Waterloo and Ohio University)

STScI-PRC06-51
Planetary Nebula Hb 5:

High resolution
Low resolution

Shaping by jets

Galaxy Cluster MS 0735.6+7421

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MS 0735.6+7421
A cluster of galaxies
The popular model in the literature (but not among massive stars) for explosion is the delayed neutrino mechanism.

Task for next two days:
Find me one paper where the delayed neutrino mechanism has achieved $1\text{f}_{\text{oe}}=1\text{B}=1\times10^{51}\text{erg}$!

One paper is enough!!
The collapse: A proto-neutron star (NS)

(from Janka et al. 2012)
The collapse

(from Janka et al. 2012)
The collapse: The stalled shock

Shock revival is a challenge in the delayed-neutrino mechanism.
The failure of the delayed-neutrino mechanism

Stalled shock
≈ 150 km

Neutrino-sphere
≈ 50 km

Heating
\[ \nu_e + n \rightarrow p + e^- \]
\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

Cooling
\[ \nu_e + n \leftarrow p + e^- \]
\[ \bar{\nu}_e + p \leftarrow n + e^+ \]
The failure of the delayed-neutrino mechanism

The delayed neutrino mechanism has 3 problems:

1. To revive the stalled shock.
2. To achieve the common energy of $1\text{f}o\text{e}=1\text{B}$
3. It cannot account for energy of more than $2\text{Be}\text{the}$. So even if the mechanism works, we need another energy source.

$1\text{B} = 10^{51}\text{erg}$
The failure of the delayed-neutrino mechanism

Problem 2 (Papish, Nordhaus, Soker 2015):

The neutrino-sphere is at $r \approx 50\text{km}$. The optical depth above the neutrino-sphere is

$$\tau_{\nu} \approx 0.1 (r/100\text{ km})^{-3}$$

The acceleration time of the shell is about the dynamical time

$$t_d \approx 20 (r/100\text{ km})^{3/2} \text{ ms}$$

The energy the accelerated gas can acquire from neutrinos

$$E_{\text{shell}} \approx t_d \tau_{\nu} L_{\nu} \approx 0.1 \left( \frac{L_{\nu}}{5 \times 10^{52} \text{ erg s}^{-1}} \right) \left( \frac{r_{\text{acceleration}}}{100 \text{ km}} \right)^{-3/2}$$

This is about 0.1 times the typical energy of supernovae
The failure of the delayed-neutrino mechanism

Problem 3:

Explosion energy in $1B=1\text{Bethe}=10^{51}$ erg

Explosion model calibrated to give the observed energy for SN 1987A and the Crab supernova using a 9.6 Mo progenitor
(from Sukhbold et al. 2016)
That the explosion energy is few times the binding energy suggests a negative feedback mechanism.

I think it is the Jet Feedback Mechanism (JFM)

See:
“The jet feedback mechanism (jfm) in stars, galaxies and clusters (a review)”
The Jet Feedback Mechanism (JFM)

We are only starting.
If the 30-years old delayed neutrino mechanism is a BMW driven by Hans-Thomas Janka, we are on a scooter.
The Jet Feedback Mechanism (JFM)

However, the core-collapse supernova community is in a traffic jam.
We suggest that core collapse supernovae are exploded by jets launched from the newly born neutron star (or black hole). This is the jet feedback mechanism.

With low angular momentum it is termed the jittering-jets model.

The goal is to reach an energy of $\mathcal{B}$

$$\mathcal{B} = 10^{51} \text{erg}$$
We suggest that core collapse supernovae are exploded by jets launched from the newly formed neutron star (or black hole). This is the jet feedback mechanism.

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The goal is to reach an energy of $B$

$$1B = 10^{51} \text{erg}$$

Two jets or not to B
Jets are not exotic!
We see jets in AGN, Young stars, Binary stars, Planetary nebulae, GRBs

KjPn8 (planetary nebula) (Lopez et al. 2000)
Ou4 (young star) (Romano Corradi)
Jets are not exotic!

We see jets in AGN, Young stars, Binary stars, Planetary nebulae, GRBs.

A mechanism based on using just 1% of the neutrino energy is exotic.

KjPn8
(planetary nebula)
(Lopez et al. 2000)

Ou4
(young star)
(Romano Corradi)
Jet-driven explosions of CCSNe have been simulated for a long time, but mainly in cases where the pre-collapsing core has both rapid rotation and strong magnetic fields.

Winteler et al. (2012): MAGNETOROTATIONALITY DRIVEN SUPERNOVAE AS THE ORIGIN OF EARLY GALAXY r-PROCESS ELEMENTS?

Figure 1. 3D entropy contours spanning the coordinates planes with magnetic field lines (white lines) of the MHD-CeSN simulation \(\sim 31\) ms after bounce. The 3D domain size is \(700 \times 700 \times 1400\) km.
Figure 2. Density and velocity maps for the $t_{\text{eng}} = 7.5$ s simulation at breakout ($t = 8.13$ s). The top panel shows a false-color rendering of the logarithm of the density, while the bottom panel shows velocity in units of the speed of light (see color scales on the right).
Figure 8. A snapshot of the central region in our fiducial 3D model M3 at $t = 4400R_L/c \sim 1.5$ s, when the jet head is at $z = 800R_L \sim 8 \times 10^9$ cm, or about 10 percent of the stellar radius. The colour scheme in the left-hand panel shows the $\log_{10}(\nabla \times B)$, which is a tracer of conduction currents, and the right-hand panel shows the $\log_{10}(\sigma)$, which is a tracer of magnetization.
The Jet Feedback Mechanism (JFM)

Motivation to consider jets:
(1) People deduce the existence of jets in long gamma ray bursts.
The Jet Feedback Mechanism (JFM)

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The Jet Feedback Mechanism (JFM)

Motivation to consider jets:
(1) People deduce the existence of jets in long gamma ray bursts.
(2) The explosion energy is several times the binding energy of the core. This hints on a negative feedback mechanism.
(3) Models to achieve energetic explosions seem to require large amount of angular momentum in the pre-collapse core, like the magnetar model.
A schematic presentation of the jittering jets mechanism in a non-rotating (or slowly rotating) core, spanning an evolution time of several seconds. (from Papish, Gilkis, Soker 2015; accepted for publication by astro-ph)

\[ \approx 500\text{km} \]
A simulation of 3-pairs of opposite jets launched within 0.15 seconds inside a core of a massive star just after the formation of the new neutron star.

A full 3D simulation. Shown at t=0.05 sec after 1 jet-launching episodes (Papish & Soker 2014)
Comparing the 3 times (from Papish & Soker 2014)
Super-energetic core collapse supernovae: magnetars and jets

- Neutrino-based mechanisms cannot account for explosion energy of \( >2\text{Bethe} \).
- Many models assume the formation of a Magnetar (rapidly rotating magnetized neutron star).
- It seems that energetic jets are inevitable during the formation process of a magnetar (Soker 2016, New Astronomy; paper was accepted to New Astronomy in less time than it was accepted by astro-ph).

Conclusion: A magnetar can definitely be formed. But jets are likely to be more energetic than the magnetar.
The 31-years old delayed neutrino mechanism has failed (a sophisticated failure) to explode core collapse supernovae with the desired energy.

There are good reasons to adopt jets: Gamma-ray bursts, the hint for a negative feedback mechanism, and super-energetic supernovae.

I call for a paradigm shift from neutrino-based explosions to jet-driven explosions for core-collapse supernovae.

Main points

- Two jets or not to B
Signatures in SNRs
A neutron star with its jets

3C58
Credit: NASA/CXC/SAO/P.Slane et al.
Crab Nebula

A neutron star with its jets

An ear

Credit: NASA/CXC/ASU/J.Hester et al

Credit: NASA, ESA, J. Hester, A. Loll (ASU);
Acknowledgement: Davide De Martin (Skyfactory)
Fig. 1. The $H_\alpha$ image of the supernova remnant S 147 (Drew et al. 2005; reproduced with permission of the IPHAS collaboration). Position of the pulsar PSR J0538+2817 is indicated by a cross. The line drawn in the east-west direction shows the bilateral symmetry axis (see text for details). North is up, east at left.
I estimate that the energy required to form the ears is 5-10% of the explosion energy.

- Area covered by the Ears: $A \sim 0.05-0.1$
- Extra kinetic energy per unit mass due to high velocity $e \sim 1$
- Extra energy: $DE \sim A*e \sim 0.05-0.1$
Formation of Ears: I think they are formed by jets

The ears can be formed before the explosion.
This requires a binary companion.
+ A bipolar circumstellar gas is seen in SN 1987A
+ S147 had a massive binary companion
  (e.g., Dincel et al. 2015).

The ears can be formed during the explosion.
This might occur in the jet-feedback mechanism. In the last episode jets are launched after the core was exploded.
These jets freely expand and form the ears.
+ Expected in the explosion mechanism.
+ Can have 5-10% of the explosion energy.
+ Same angular momentum spins-up the newly born neutron star.

The ears can be formed after the explosion.
+ We observe jets from the pulsar at the center (A note about magnetars).
  ? Does the pulsar have 5-10% of the explosion energy released in jets?
  (In 3C58 only ~1e49 erg in the pulsar.)
Super-energetic core collapse supernovae: magnetars and jets

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Conclusion: A magnetar can definitely be formed. But jets are likely to be more energetic than the magnetar.

I expect jets in the formation process of rapidly rotating neutron stars.
Cassiopeia A

In blue: 44Ti
In Green: Si

A possible explanation in the frame of the jittering jets scenario.

- The 44Ti is formed at early times — first several jets. 44Ti spreads sporadically in inner regions.

- The last jets-launching episode did not collide with dense core gas, hence no 44Ti is formed. These jets expand to large distances.

(Grefenstette et al. 2014)
A religious person is drowning in the flood.

Someone throw him a rescue wheel.
“No, thanks. God will help me”, he says.

People in a boat suggest help.
“No, thanks. God will help me”, he says.

A helicopter with rope ladder comes.
“No, thanks. God will help me”, he says.

Eventually he dies in the flood. When he arrives to heaven he asks God:
“Why didn’t you rescue me?”
God replies: “I sent you a rescue wheel, a boat and a helicopter; what else did you want me to do?”
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A researcher working on the explosion mechanism of core collapse supernovae gets (at a good age and after using trillions of cpu-hours) to heaven. He asks God:

“Why didn’t you tell us how supernovae explode?”

God replies:

“I failed you for more than 30 years in exploding massive stars with neutrinos, I sent you Gamma Ray Bursts with their jets, I sent you SNR with ‘Ears’ and jets, I exploded super-energetic SNe that you cannot explain with neutrinos; what else did you want me to do?”
Ears in planetary nebulae
Simulations of jets
(Tsebrenko & Soker 2013, 15)

Ears in Type Ia SNRs

G1.9+0.3 SNR
(poster by Stephen Reynolds)

Numerical simulations of a SN Inside a Planetary nebula (SNIP)
(from Tsebrenko, D. & Soker, N. 2015)
Ears in Type Ia SNRs

Kepler SNR: ~1Mo CSM

G1.9+0.3 SNR

G299-2.9 SNR
JETS !?

Simulations of jets by Danny Tsebrenko
Jets might be common in pre-SN Ia,
(Tsebrenko & Soker 2013, 2015)

SNIP:
Supernovae Inside Planetary nebulae
The existence of `Ears’

Two jets or not to be
Here is a slide from the talk (Friday) by **Alexandros Chiotellis**. Interaction of a SN Ia with a bipolar PN $\rightarrow$ ‘lobes’ (‘Ears’) in the equatorial plane. We find ears in the poles!! See also Burkey et al. 2013 who also take the equatorial plane to be where we take the symmetry axis (polar directions) in Kepler SNR.
SNR morphologies and circumstellar-matter (CSM) can be used to examine scenarios of SN IIa (Wolfgang Kerzendorf talk)
<table>
<thead>
<tr>
<th>Supernovae</th>
<th>Property</th>
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<tbody>
<tr>
<td><strong>PTF11kx</strong></td>
<td>Core Degenerate Scenario fits the best</td>
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<tr>
<td></td>
<td>( M_{\text{CSM}} \approx 0.8 \left( \frac{\text{CSM size}}{1000\text{AU}} \right)^{3/2} ) ( M_e )</td>
</tr>
<tr>
<td><strong>Kepler SNR</strong></td>
<td>No giant left ! (Wolfgang Kerzendorf)</td>
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<tr>
<td></td>
<td>A SNIP shaped by jets *</td>
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<tr>
<td><strong>G1.9+0.3 (X-ray)</strong></td>
<td>A SNIP shaped by jets *</td>
</tr>
<tr>
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<td>(SNIP: Supernova inside Planetary nebula)</td>
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<tr>
<td></td>
<td>• In 2015: or by iron bullets (Tsebrenko &amp; Soker 2015)</td>
</tr>
<tr>
<td><strong>SN 1006</strong></td>
<td>Elliptical remnants</td>
</tr>
<tr>
<td><strong>SNR 0509</strong></td>
<td>• ( R_{\text{WD}} &lt; 0.02R_e )</td>
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<tr>
<td><strong>SN 1572</strong></td>
<td>• 98% carbon in fastest ejecta</td>
</tr>
<tr>
<td><strong>SN 2011fe</strong></td>
<td>• No close CSM</td>
</tr>
<tr>
<td><strong>CD Scenario fits the best</strong></td>
<td>• Strong limits on a companion</td>
</tr>
</tbody>
</table>
There are 5 (or even 6) scenarios for SN Ia

When one examines the observations, no scenario is free of problems.

The single-degenerate and the double degenerate scenarios are the oldest. I think the core-degenerate scenario does the best.

<table>
<thead>
<tr>
<th>Core Degenerate</th>
<th>Double Degenerate</th>
<th>Double Detonation</th>
<th>Single Degenerate</th>
<th>WD-WD collision</th>
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<td>Presence of two opposite Ears in some SNR Ia.</td>
<td>≈ 1M⊙ CSM in Keplers SNR + Na lines</td>
<td>Main Scenario Predictions</td>
<td>General Strong Characteristics</td>
<td>General Difficulties</td>
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<td>Severe Difficulties</td>
<td>Fraction of SN Ia (TS2015)</td>
<td>My suggestion</td>
<td></td>
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<tr>
<td>Explained by SNIP (Supernovae inside planetary nebulae [PN]) (TS2015).</td>
<td>Low mass Ears if jets during merger (TS2013).</td>
<td>No Ears are expected for He WD companion.</td>
<td>Ears by jets from accreting WD or iron bullets (Tsebrenko &amp; Soker, 15)</td>
<td>No Ears are expected</td>
</tr>
<tr>
<td>≈ 1M☉ CSM in Keplers SNR + Na lines</td>
<td>The massive CSM might be a planetary nebula.</td>
<td>No CSM shell</td>
<td>Any CSM is of a much lower mass</td>
<td>Might be explained by heavy mass loss from an AGB donor.</td>
</tr>
</tbody>
</table>

Main Scenario Predictions

- 1. Single WD Exp.
- 2. Massive CSM in some cases (SNIP)

General Strong Characteristics

- 1. Explains some SN Ia with H-CSM
- 2. Symmetric Exp.

General Weak Characteristics

- 1. Explains very well the delay time distribution (DTD)
- 2. Asymmetrical explosion

General Difficulties

- More work on
  - 1. Ignition process
  - 2. DTD
  - 3. Merge during CE
  - 4. Find massive WDs

Severe Difficulties

- 1. MWD < 1.2M☉
- 2. Highly asymmetrical Exp.

Fraction of SN Ia (TS2015)

- > 20%
- < 80%
- < few × % (Piersanti et al. 2013)
- 0%

My suggestion

- “normal SN Ia” > 85%
- Weak SN Ia < 15%
- Peculiar transients, not SN Ia
- Some Really Strong Novae (WD survives).

Rare events—if at all
Summary

Jets shape some supernova remnants. Prominent is the existence of `Ears':

**Two jets or not to be**

This might support the jet-feedback mechanism for exploding massive stars.

**Two jets or not to be B**

This might support the explosion of some SN Ia inside a Planetary Nebula

**SNIP**

SNIP is compatible with the Core-Degenerate (CD) Scenario for SN Ia