Neutrino signatures of the incoming core-collapse supernova

Andrzej Odrzywolek

Department of General Relativity and Astrophysics
Jagiellonian University, Cracov, Poland

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Everybody here would like to know . . .

But no one knows . . .

Why?
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When next supernova in the Galaxy will explode?

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Why?

Why we can’t answer this ”simple” question?
Why we are unable to estimate time remaining to the core-collapse with accuracy better than 100 000 years, even for nearest candidate, Betelgeuse at distance of only 130 parsecs?

1. Core evolution decouples from surface evolution
2. Core size \((R_c \sim 10^4 \text{ km})\) vs surface \((R_s \sim 10^7 \ldots 10^9)\)
3. Evolution is too fast \(\tau \sim 100\) years
4. No C burning star is known
When next supernova in the Galaxy will explode?

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3. Evolution is too fast $\tau \sim 100$ years
4. No C burning star is known

- all the above is due to neutrinos!
- **Solution**: direct and indirect (?) $\nu$ detection
Informations on $\nu$ emission in the course of pre-SN life

Stellar life for neutrino astronomer

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\langle L_\nu \rangle$ [erg/s]</th>
<th>$E_\nu^{\text{tot}}$ [erg]</th>
<th>Time [yrs]</th>
<th>$\langle E_\nu \rangle$ [MeV]</th>
<th>Process</th>
<th>Flavors</th>
</tr>
</thead>
<tbody>
<tr>
<td>H burning</td>
<td>$10^{36}$</td>
<td>$10^{52}$</td>
<td>$10^7$</td>
<td>0.5-1.7</td>
<td>CNO</td>
<td>$\nu_e$</td>
</tr>
<tr>
<td>He burning</td>
<td>$10^{31}$</td>
<td>$10^{49}$</td>
<td>$10^6$</td>
<td>0.02</td>
<td>plasma</td>
<td>all</td>
</tr>
<tr>
<td>$\nu$-Cooled</td>
<td>$10^{38}$ - $10^{46}$</td>
<td>$10^{51}$</td>
<td>$10^4$</td>
<td>0.5-1.5</td>
<td>pair</td>
<td>all</td>
</tr>
<tr>
<td>Neutronization</td>
<td>$10^{54}$</td>
<td>$10^{51}$</td>
<td>$10^{-2}$</td>
<td>10</td>
<td>$\epsilon^-$</td>
<td>$\nu_e$</td>
</tr>
<tr>
<td>SN neutrinos</td>
<td>$10^{52}$ - $10^{48}$</td>
<td>$10^{53}$</td>
<td>10 sec</td>
<td>10-40</td>
<td>$\nu$ transport</td>
<td>all</td>
</tr>
<tr>
<td>NS cooling</td>
<td>$&lt; 10^{48}$</td>
<td>$&lt; 10^{51}$</td>
<td>$10^4$</td>
<td>1</td>
<td>d(m)URCA</td>
<td>$\nu_e$, $\bar{\nu}_e$</td>
</tr>
</tbody>
</table>

1. detection of the $\nu$'s from core-collapse within the Galaxy is no longer a challenge now

2. focus should be redirected for shock breakout $\nu_e$ pulse, late cooling of neutron stars and Neutrino-Cooled stage of pre-supernova
Before and after core-collapse

Workshop Towards $\nu$ Technologies, 13-17 July 2009, Trieste

A. Odrzywolek, $\nu$ signatures of the incoming supernova
Final stages of the 15 $M_{\odot}$ pre-supernova star (s15)

Typical sequence of events leading to the core-collapse supernova with important sources of the $\nu$’s.
Neutrino flux 100 years before supernova explosion

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A. Odrzywolek, $\nu$ signatures of the incoming supernova
\( \langle E_\nu \rangle \) 100 years before supernova explosion
Possible detectable signatures of the incoming SN

Prominent neutrino features of the 15 M☉ star

1. core/shell O burning (months before core-collapse)
   - detection limited to Betelgeuse \( (d = 100 \ldots 200 \text{ pc}) \)

2. core Si burning (8 - 0.5 days before core-collapse)
   - for stars closer than 1-2 kpc

3. max. contraction and shell Si burning (2-0.5 hours b.c.)
   - up to 10 kpc

4. direct pre-collapse stage (30 - 0 minutes b. c.)
   - this should be considered as an initial stage of the core-collapse, as most of \( \nu_e \) come in last minutes with smooth transition to neutronization peak

[cf. previous talk of W. Fulgione]

Both pair annihilation \( \bar{\nu}_e \) and electron capture on nuclei \( \nu_e \) are sources of detectable events.
Pre-supernova $\bar{\nu}_e$ spectra vs geo-neutrinos

Black - geoneutrino $\bar{\nu}_e$ spectrum
(Sanhiro Enomoto PhD)
Red - thermal pre-SN spectrum:
  pair + plasma
Blue - weak pre-SN spectrum:
  $e^-$ capture for $\alpha$-network nuclei for $kT<0.4$ MeV
  NSE neutrinos for $kT>0.4$ MeV

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Core Si burning, 2.00 days B.C.

Distance = 100 pc

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(arXiv:0903.2311v1)
Pre-supernova $\bar{\nu}_e$ spectra vs geo-neutrinos

Shell Si burning, 1.72 hours B.C.

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Pre-supernova $\nu_e$ spectra vs solar neutrinos

Shell Si burning, 1.72 hours B.C.

Distance = 1 kpc

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(arXiv:0903.2311v1)
Signal expected in Liquid Scintillator detector

Signal in LS detector with $E_{th}=0.2$ MeV

Distance = 10 kpc

Event rate in $H_2O$ [kiloton$^{-1}$ s$^{-1}$]

Solar $^8B\nu_e$ level

Geo $\bar{\nu}_e$ level

Red – Inv. $\beta$ ($\bar{\nu}_e$)

Blue – Elastic scattering ($\nu_e$)

Time B.C. [seconds]

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Signal in LS detector with $E_{th} = 0.2$ MeV

Distance = 1 kpc

- Solar $^8\text{B} \gamma_e$ level
- Geo $\bar{\nu}_e$ level
- Red – Inv. $\beta (\bar{\nu}_e)$
- Blue – Elastic scattering ($\nu_e$)

Event rate in $H_2O$ [kiloton$^{-1}$ s$^{-1}$] vs. Time B.C. [seconds]

Ev. rate [kiloton$^{-1}$ day$^{-1}$] vs. Time B.C. [seconds]

Shell Si
Core Si

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A. Odrzywole, $\nu$ signatures of the incoming supernova
Signal expected in Water Cherenkov detector

Signal in WC detector with $E_{th}=4$ MeV

Distance = 10 kpc

Solar $^8$B $\nu_e$ level
Geo $\bar{\nu}_e$ level

Red – Inv. $\beta$ ($\bar{\nu}_e$)
Blue – Elastic scattering ($\nu_e$)

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Event rate in H$_2$O [kiloton$^{-1}$ s$^{-1}$]

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Geo $\overline{\nu}_e$ level

Red – Inv. $\beta$ ($\overline{\nu}_e$)

Blue – Elastic scattering ($\nu_e$)

Ev. rate [kiloton$^{-1}$ day$^{-1}$]

Time B.C. [seconds]

Shell Si

Core Si
Warning scenario Ia: shell Si burning (0.5 Mt WC detector)

1-Hour moving window signal from 10 kpc

Both $\nu_e$ (ES) and $\bar{\nu}_e$ (IBD) signals provide $\sim$1 hour warning of the CC SN in 0.5 Mt class WC detector from 10 kpc

Simultaneous $\nu_e + \bar{\nu}_e$ positive fluctuation are of low probability
Both $\nu_e$ (ES) and $\bar{\nu}_e$ (IBD) signals provide $\sim 1$ hour warning of the CC SN in 0.5 Mt class WC detector from 10 kpc. Simultaneous $\nu_e + \bar{\nu}_e$ positive fluctuation are of low probability.
Warning scenario Ib: shell Si burning (Super-Kamiokande)

$\nu_e$ (ES) and $\bar{\nu}_e$ (IBD) signals provide clear $\sim 1$ hour warning in Super-Kamiokande from 1 kpc.
\( \nu_e \) (ES) and \( \bar{\nu}_e \) (IBD) signals provide clear \( \sim1 \) hour warning in Super-Kamiokande from 1 kpc
Warning scenario Ic: shell Si burning (LENA)

1-Hour moving window signal from 10 kpc

1. $\nu_e$ (ES) signal provide clear $\sim$1 hour warning in LENA from 10 kpc

2. Inv. $\beta$ negligible, only 0-2 hits expected
Warning scenario II: core Si/O burning

**NOTE:** this is limited only to nearby stars at distance $d \ll 10$ kpc.

Daily binned signal from Betelgeuse ($d=130$ pc)
What can be expected from other stellar models?
How generic Si core/shell burning signature is?

Evolutionary sequence for other massive stars

- two full outputs for 15 M\(_\odot\) and 25 M\(_\odot\) pre-supernovae has been thoroughly analysed: both provide core Si/shell Si signals
- presented case should be typical
- known exceptions are:
  - stars in the range of initial mass 8-11 M\(_\odot\) might do not enter O and Si burning stages before collapse
  - some stars might collapse without entering shell Si burning
  - on the other way, two shell Si burning stages are possible

25 M\(_\odot\) versus 15 M\(_\odot\) pre-supernova

- evolution of 25 M\(_\odot\) is much faster, so \(\nu\) flux is therefore higher
- neutrinos are emitted under less degenerate conditions and have smaller energies: detected signals are lower
- more massive stars are less numerous (IMF)
Conclusions

- pre-supernova produces steadily increasing $\nu_e$ and $\bar{\nu}_e$ flux with progressively higher energy
- new results now include weak nuclear neutrinos: strong (up to $100 \times$ pair) $\nu_e$ flux after core Si ignition has been calculated in addition to previously known thermal $\bar{\nu}_e$ flux
- energy of $\nu_e$ is estimated using FFN rates from $\alpha$-network ($\sim 4$ MeV) and NSE ($\sim 2.5$ MeV)
- evolutionary processes: core/shell O, core Si, shell Si burning and direct pre-collapse contraction provide sequence of events in the neutrino detectors
- detection possibility highly depends on the distance; for nearby Betelgeuse future LS detectors (LENA) are able to detect $\nu_e$ flux months before supernova
- 50% of Galactic stars lie within distance of 10 kpc; from this distance we can detect only shell Si burning $\sim 1$ hour B.C.
- terrestrial $\bar{\nu}_e$ and solar $\nu_e$ are main irremovable backgrounds; directional analysis can possibly help
Important References

- **Stellar models s15 and s25:** Woosley, S. E.; Heger, A.; Weaver, T. A., *The evolution and explosion of massive stars*, Reviews of Modern Physics, 2002 74, 1015-1071

- **Neutrino spectra & basic processes:** Misiaszek, M.; Odrzywolek, A.; Kutschera, M., *Neutrino spectrum from the pair-annihilation process in the hot stellar plasma*, Physical Review D, 74, 043006.


- **Protoneutron star neutrino cooling and delayed black hole formation:**
PSNS WWW devoted to post-processing of astrophysical models with focus on detailed state-of-art neutrino spectra:
http://ribes.if.uj.edu.pl/psns
Comparison of the solar $\nu_e$ spectrum and pre-supernova from 1 kpc (left) and geoneutrinos at Kamioka with pre-supernova $\bar{\nu}_e$. Animation show last 40,000 years before supernova, after end of the He burning.

Animation link
Definition of **massive star**

- star massive enough to explode as a core-collapse supernova
- lower range end is not precisely known: $8-11 \, M_\odot$
- I will talk about „genuine” massive stars $M > 15 \, M_\odot$
- particularly, analysed stars enter **core** and **shell** $Si$ burning stages
- two complete stellar models: s15 and s25 of A. Heger are used to examine detection scenarios
- *real-world* examples: *Betelgeuse, Eta Carinae*