Development of the pre-supernova neutrinos

Andrzej Odrzywołek

M. Smoluchowski Institute of Physics, Jagiellonian U. in Kraków, Poland

Revealing the history of the universe with underground particle and nuclear research
13:50, Saturday 9 March 2019
Can we see neutrinos from other/distant "regular" stars?

The Sun is excluded from now ...
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Early thoughts

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<table>
<thead>
<tr>
<th>Burning Stage</th>
<th>Central Temperature (K)</th>
<th>Central Density (g cm$^{-3}$)</th>
<th>Neutrino Luminosity$^\dagger$ (erg s$^{-1}$)</th>
<th>Optical Luminosity (erg s$^{-1}$)</th>
<th>Effective Temperature (K)</th>
<th>Photospheric Radius (cm)</th>
<th>Time Scale (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>3.4 (7)</td>
<td>5.9 (0)</td>
<td>---</td>
<td>8.1 (37)</td>
<td>3.26 (4)</td>
<td>3.2 (11)</td>
<td>3.9 (14)</td>
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<tr>
<td></td>
<td>3.7 (7)</td>
<td>3.8 (0)</td>
<td>---</td>
<td>3.1 (38)</td>
<td>3.98 (4)</td>
<td>4.2 (11)</td>
<td>2.3 (14)</td>
</tr>
<tr>
<td>Helium</td>
<td>1.6 (8)</td>
<td>1.3 (3)</td>
<td>3.9 (33)</td>
<td>2.3 (38)</td>
<td>1.59 (4)</td>
<td>2.2 (12)</td>
<td>4.2 (13)</td>
</tr>
<tr>
<td></td>
<td>1.8 (8)</td>
<td>6.2 (2)</td>
<td>7.3 (34)</td>
<td>9.5 (38)</td>
<td>1.58 (4)</td>
<td>4.7 (12)</td>
<td>2.1 (13)</td>
</tr>
<tr>
<td>Carbon</td>
<td>6.2 (8)</td>
<td>1.7 (5)</td>
<td>3.4 (38)</td>
<td>3.3 (38)</td>
<td>4.26 (3)</td>
<td>3.7 (13)</td>
<td>2.0 (11)</td>
</tr>
<tr>
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<td>7.2 (8)</td>
<td>6.4 (5)</td>
<td>1.0 (40)</td>
<td>1.2 (39)</td>
<td>4.36 (3)</td>
<td>6.7 (13)</td>
<td>5.2 (9)</td>
</tr>
<tr>
<td>Neon</td>
<td>1.3 (9)</td>
<td>1.6 (7)</td>
<td>6.7 (41)</td>
<td>3.7 (38)</td>
<td>4.28 (3)</td>
<td>3.9 (13)</td>
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</tr>
<tr>
<td></td>
<td>1.4 (9)</td>
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<td>7.8 (42)</td>
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<tr>
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$^\dagger$All physical parameters refer to conditions just after the core ignition of each fuel, except the time scale which is the period between successive ignitions. The value for the 15 $M_\odot$ star is listed first in each case.

$^\dagger$Excluding neutrino losses during hydrogen burning.
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10 years of progress (theory side)


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- Pair neutrino "light" curves (from piecewise-const to time-integration)

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- Other thermal production channels (photo, plasma, deexcitation)

- Effects of neutrino oscillations

- Hydro O/Si burn (last 150 sec)

- Modern stellar evolution codes [see next talk] vs. current O/Ne/Mg envelope treatment

- ONeMg vs Si-burning pre-supernovae
  Kato et. al. (2016-2017)

- Consistent post-processing of MESA stellar models with $\beta^\pm$ processes
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![Graph of Ye (25 solar masses star)](image)


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modern stellar evolution codes [see next talk] versus past pre-supernova concern

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![Electron neutrino luminosity (s12 model)](image1)
![Electron anti-neutrino luminosity (s12 model)](image2)

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Recent progress (detector side)

- EGADS — Kamiokande with gadolinium (all tests completed with 100% success)
- Super-Kamiokande with Gd$_2$(SO$_4$)$_3$ — SK-Gd starting 2020 [Mark Vagins morning talk]
- DUNE LAr detector [Maury Goodman talk from previous session]
- Hyper-Kamiokande project starting construction next year, operating 2027 [Takatomi Yano talk]
- other low threshold (below ∼ 2 MeV) large detectors: JUNO, Borexino, coherent, DM search . . .

Pre-supernova warning: from sci-fi to reality in 20 years?

Any day now, nearby (d ≪ 1 kpc) Galactic supernova could be observed via neutrinos in full time-extent, starting from Si burning week before collapse until late neutron star colling or black hole formation.

In the meantime, gravitational wave astronomy (GW 170817) and neutrino astronomy (SN 1987A) tied in observation of "precious" (not only because of gold&gadolinium production) events... they stay at the same place we did afters 1987.
Typical neutrino light curve for 15 $M_\odot$ star
What could be missing in pre-sn neutrino calculations?

Standard procedure

We take a single stellar model (2-3 models at best), then "fire everything we have":

- do detailed stellar evolution
- integrate all timesteps & all zones of the model
- use the biggest nuclear network/NSE limited only by hardware/nuclear data
- use the most precise neutrino spectrum calculations
- include neutrino oscillations
- ...

Then we say: number of events in detector X from distance D will be N . . .

Is this procedure stable?

What if we do, e.g:

1. change initial (ZAMS) mass by $\pm 2 \text{ M}_\odot$,
2. increase/decrease metallicity $Z$ by 0.005,
3. switch the stellar wind ON/OFF
4. modify nuclear reaction network by adding 3 or 100 isotopes?
Reference MESA model

1. $M_{\text{ZAMS}} = 16M_\odot$
2. $Z = 0.015$ (+0.05 dex for Betelgeuse using $Z_\odot = 0.0134$)
3. no stellar wind (mass loss zero)
4. standard MESA auto-extended nuclear reaction network:
   - H and He burning: basic.net
   - C/O burning: co_burn.net
   - Si burning: approx21.net

Is the neutrino emission from this model stable with respect to "small" perturbations of the above parameters: $M_{\text{ZAMS}}$, $Z$, wind, networks?
Reference model vs ZAMS mass perturbation

- ALL models end with $1.5 \pm 0.02 \ M_\odot$ Fe core
- more massive model more luminous
- perturbation $-2M_\odot$ cannot be considered small (ONeMg collapse?)

Tohoku U., Sendai, Japan, 7-9 March 2019
Doubled/tripled shell Si-burn peaks?
Reference model vs wind (on/off/enhanced)

- final stellar mass is: 16, 14.96, and 4.67 $M_\odot$
- despite extreme wind induced by production of intermediate mass metals during shell H/He burn enhanced CNO network, final core evolution is still very similar
Reference model vs nuclear reaction network

Last peak "smeared out"

- 16Msun_Z_0015_wind_adv_net_mesa_80
- 16Msun_Z_0015
- 16Msun_Z_0015_wind_adv_net_mesa_67

"Unstable" neutrino emission

log_{10}(L/L_\odot)

10^{46}\text{erg/s}

10^{45}\text{erg/s}

1 h 3 h 6 h 12 h Time Before Collapse

Tohoku U., Sendai, Japan, 7-9 March 2019
Narrow, prominent nuclear neutrino peaks
Conclusions

- our pre-SN neutrino signal properties verified independently by several groups (Japan, USA) in 2015-2018
- neutrino signal calculations stable with respect to small perturbations of mass, metallicity and wind
- reaction network type and size might affect pre-SN signal, especially in nuclear sector; systematic study required
- "ultimate" hydrostatical modelling of pre-SN available; hydrodynamic modelling attempts made
- KamLAND pre-SN early warning works, SK-Gd project on finish
- my wishlist for future: spectral $\nu$ emission computed directly from stellar evolution code (without post-process) from H to Si burn, hydro simulation of Si burn, and last but not least: Galactic supernova!
Conclusions

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- Reaction network type and size might affect pre-SN signal, especially in nuclear sector; systematic study required.
- "Ultimate" hydrostatical modelling of pre-SN available; hydrodynamic modelling attempts made.
- KamLAND pre-SN early warning works, SK-Gd project on finish.
- My wishlist for future: spectral $\nu$ emission computed directly from stellar evolution code (without post-process) from H to Si burn, hydro simulation of Si burn, and last but not least: Galactic supernova!

ありがとうございました
Selected references


[2] J. Bahcall, Neutrino Astrophysics, §6.5 Fluxes from other stars


Neutrino spectra animation
Reference stellar model animation
Precision of the thermal neutrino calculations

Total thermal neutrino luminosity error

PSNS/MESA

Timestep

2600  2800  3000  3200  3400
Photon & neutrino HR diagram
Inverted $\nu$ mass hierarchy (s12 model)

$\log L_{\nu}$ [erg s$^{-1}$]

$10^{42}$ to $10^{48}$

Time B.C.

$10$ yr $1$ yr $100$ d $10$ d $1$ d $3$ h $1$ h $10$ min

$\nu_e$ (dotted line)
$\bar{\nu}_e$ (solid line)
$\nu_\mu$ (dashed line)
$\bar{\nu}_\mu$ (dash-dotted line)
MSW effect in H envelope leads to flavor exchange:

\[
\begin{align*}
F_{\nu_e}^{\text{osc}} &= p & F_{\nu_e} + (1-p) & F_{\nu_\mu} \\
F_{\nu_\mu}^{\text{osc}} &= (1-p) & F_{\nu_e} + p & F_{\nu_\mu} \\
F_{\bar{\nu}_e}^{\text{osc}} &= \bar{p} & F_{\bar{\nu}_e} + (1-\bar{p}) & F_{\bar{\nu}_\mu} \\
F_{\bar{\nu}_\mu}^{\text{osc}} &= (1-\bar{p}) & F_{\bar{\nu}_e} + \bar{p} & F_{\bar{\nu}_\mu}
\end{align*}
\]

Depending on mass hierarchy of neutrinos coefficients are:

\[
p = \begin{cases} \\
\sin^2 \theta_{13} \simeq 0.02 \\
\sin^2 \theta_{12} \cos^2 \theta_{13} \simeq 0.30
\end{cases} \quad \bar{p} = \begin{cases} \\
\cos^2 \theta_{12} \cos^2 \theta_{13} \simeq 0.68 \quad \text{Normal} \\
\sin^2 \theta_{13} \simeq 0.02 \quad \text{Inverted}
\end{cases}
\]