Some New Results on Stellar Neutrinos

Ebraheem Farag (ASU)
Mainak Mukhopadhyay (ASU)
Kelly Patton (Colby)
Rob Farmer (Amsterdam)
Morgan Taylor (ASU)
Cecilia Lunardini (ASU)
Kai Zuber (TU Dresden)
fxt (asu)
Roadmap

38 Slides

1) Two public service announcements
2) Neutrino astronomy
3) Neutrino production in stars
4) MESA
5) A neutrino HR diagram
6) Probing the presupernova isotopic evolution
7) Identifying the presupernova progenitor
8) Low mass stars count too!
Betelgeuse - still there.
Over the next decade, neutrino astronomy will probe the rich astrophysics of neutrino production in the sky.
In addition to the Sun, supernova 1987A, and blazar TXS 0506+056,
Super-Kamiokande with Gadolinium, Jiangmen Underground Neutrino Observatory, XENON and other experiments usher in a new generation of multi-purpose neutrino detectors designed to open new avenues for potentially observing currently undetected neutrinos.

JUNO aims to begin taking data in 2020.

XENON dark matter project

Super-K with Gadolinium Test Facility

Original detectable signal

New signal

Gadolinium

\(\text{P} \rightarrow \text{N} \rightarrow \gamma\text{-ray} \rightarrow \text{Gadolinium} \)
Supernova detection is a major objective of the Super-Kamiokande (SK) experiment. In the next stage of SK (SK-Gd), gadolinium (Gd) sulfate will be added to the detector, which will improve the ability of the detector to identify neutrons. A core-collapse supernova will be preceded by an increasing flux of neutrinos and anti-neutrinos, from thermal and weak nuclear processes in the star, over a timescale of hours; some of which may be detected at SK-Gd. This could provide an early warning of an imminent core-collapse supernova, hours earlier than the detection of the neutrinos from core collapse. Electron anti-neutrino detection will rely on inverse beta decay events below the usual analysis energy threshold of SK, so Gd loading is vital to reduce backgrounds while maximising detection efficiency. Assuming normal neutrino mass ordering, more than 200 events could be detected in the final 12 hours before core collapse for a 15-25 solar mass star at around 200 pc, which is representative of the nearest red supergiant to Earth, α-Ori (Betelgeuse). At a statistical false alarm rate of 1 per century, detection could be up to 10 hours before core collapse, and a pre-supernova star could be detected by SK-Gd up to 600 pc away. A pre-supernova alert could be provided to the astrophysics community following gadolinium loading.

Sensitivity of Super-Kamiokande with Gadolinium to Low Energy Anti-neutrinos from Pre-supernova Emission
C. Simpson et al, The Super-Kamiokande Collaboration

ABSTRACT
Celes
eq 0.6 kpc 0.4 kpc

O,B,A K M Name (M⊙, kpc)

Spica (11,0.08)
12Peg (5,0.42)
_Cyg (19,0.80)
V424 Lac (7,0.63)
HR 8248 (6,0.75)
V809 Cas (8,0.73)
HR 861 (9,0.64)
VV Cep (11,0.59)
V381 Cep (8,0.73)

145 CMa (8,0.70)
CMA (12,0.51)
\( \zeta \) Mon A (29,0.28)
\( \zeta \) Mon B (21,0.28)
CE Tauri (14,0.33)

\( \xi \) Peg (12,0.31)
\( \xi \) Cep (10,0.26)
\( \xi \) Cyg (8,0.28)

\( \zeta \) Ori (12,0.22)
\( \alpha \) Ori (21,0.26)

HR 3692 (12,0.65)
\( \lambda \) Del (6,0.63)
\( \theta \) Del (6,0.63)
HR 8248 (6,0.75)
V809 Cas (8,0.73)

Mukhopadhyay et al 2020
Let’s explore recent theoretical results that provide

New targets for current, forthcoming, and future generations of neutrino detectors,

New estimates of the stellar neutrino background signal,

New opportunities for nuclear experiments that can make sizable differences in stellar evolution.
Neutrino Production in Stars
Stars radiate energy by releasing photons from the stellar surface and neutrinos from the stellar interior.

\[ \sigma_\nu \simeq \left( \frac{E_\nu}{m_e c^2} \right)^2 \cdot 10^{-44} \text{ cm}^2 \]

\[ \sigma_\gamma = \frac{8\pi}{3} \left( \frac{\alpha \hbar c}{m_e c^2} \right)^2 \simeq 10^{-24} \text{ cm}^2 \]

\[ \lambda_\nu = \frac{m_u}{\rho \cdot \sigma_\nu} \bigg|_{\odot} \simeq 3 \cdot 10^{19} \text{ cm} \simeq 10 \text{ pc} \simeq 4 \cdot 10^9 R_\odot \]

\[ \tau_\nu \simeq R_\odot / c \simeq 2 \text{ s} \]
Weak reactions produce electron neutrinos by thermal processes

pair neutrino: \( e^+ + e^- \rightarrow \nu + \bar{\nu} \)

photoneutrino: \( e^- + \gamma \rightarrow e^- + \nu + \bar{\nu} \)

plasmon neutrino: \( \gamma_{\text{plasmon}} \rightarrow \nu + \bar{\nu} \)

bremsstrahlung: \( e^- + N(Z, A) \rightarrow e^- + N(Z, A) + \nu + \bar{\nu} \)

recombination: \( e^-_{\text{continuum}} \rightarrow e^-_{\text{bound}} + \nu + \bar{\nu} \)
Weak reactions produce neutrinos from β-processes

Electron captures:

\[ ^A Z + e^- \xrightarrow{W^\pm} ^A (Z - 1) + \nu_e \]
\[ p + e^- \xrightarrow{W^\pm} n + \nu_e \]

Positron captures:

\[ ^A Z + e^+ \xrightarrow{W^\pm} ^A (Z + 1) + \bar{\nu}_e \]
\[ n + e^+ \xrightarrow{W^\pm} p + \bar{\nu}_e \]

Electron emission (β- decay):

\[ ^A Z \xrightarrow{W^\pm} ^A (Z + 1) + e^- + \bar{\nu}_e \]
\[ n \xrightarrow{W^\pm} p + e^- + \bar{\nu}_e \]

Positron emission (β+ decay):

\[ ^A Z \xrightarrow{W^\pm} ^A (Z - 1) + e^+ + \nu_e \]
\[ p \xrightarrow{W^\pm} n + e^+ + \nu_e \]

Deexcitation:

\[ ^A Z \xrightarrow{Z^0} ^A Z + \nu + \bar{\nu}_e \]
A Stellar Evolution Instrument
The MESA source code is a set of software modules for stellar astrophysics that can be used on their own, or combined to solve the coupled equations governing 1D stellar evolution with an implicit finite volume scheme.
Citations: 3,419

Citations to papers that cite MESA: 45,645

MESA I - Top 5 in 2011
MESA II - Top 10 in 2013
MESA III - Top 10 in 2015
MESA IV - Top 30 in 2018

Data from SAO/NASA ADS
The Summer School cadre of instructors, TAs and participants (now over 400) are creating their own MESA user infrastructure at ~50 institutions around the world.
MESA Stellar Models
Solar Neutrino Fluxes

<table>
<thead>
<tr>
<th>Component</th>
<th>AGSS09</th>
<th>GS98</th>
<th>Observed$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_{pp}$</td>
<td>6.01</td>
<td>5.98</td>
<td>$6.05(1^{+0.003}_{-0.011})$</td>
</tr>
<tr>
<td>$\Phi_{Be}$</td>
<td>4.71</td>
<td>4.95</td>
<td>$4.82(1^{+0.05}_{-0.04})$</td>
</tr>
<tr>
<td>$\Phi_{B}$</td>
<td>4.62</td>
<td>5.09</td>
<td>$5.00(1 \pm 0.03)$</td>
</tr>
<tr>
<td>$\Phi_{N}$</td>
<td>2.25</td>
<td>2.91</td>
<td>$\leq 6.7$</td>
</tr>
<tr>
<td>$\Phi_{O}$</td>
<td>1.67</td>
<td>2.21</td>
<td>$\leq 3.2$</td>
</tr>
</tbody>
</table>

$^a$Neutrino observations from the Borexino Collaboration (Bellini et al. 2011) as presented in Haxton et al. (2013) and Villante et al. (2014). The scales for neutrino fluxes $\Phi$ (in cm$^{-2}$ s$^{-1}$) are: $10^{10}$ (pp); $10^{9}$ (Be); $10^{6}$ (B); $10^{8}$ (N); and $10^{8}$ (O).

Farag et al 2020

$$L_{\nu,\odot} = 0.024 \cdot L_{\gamma,\odot} = 9.18 \times 10^{31} \text{ erg/s}$$
The ~110 year old classic HR Diagram.

One doesn’t mess with a classic ...

... but what if ...

Farag et al 2020
A neutrino HR Diagram!
When do thermal or $\beta$-processes dominate?

Reactions tend to dominate whenever H or He burns.
Neutrinos tend to dominate at the end of star’s life.
Probing the evolution of pre-supernova models
The march to core-collapse.
β-process rates that matter. Isotopes listed for neutrinos are mainly electron captures, those for antineutrinos are mainly β⁻ decay. We encourage new experiments and theory!

Patton et al 2017

chiefly $A = 50-60$

Log \( \rho_c / \text{g cm}^{-3} \)

Log \( T_c / \text{g cm}^{-3} \)

15 M⊙

E₉ ≥ 2 Mev

νₑ

53Fe - 17%
55Fe - 15%
55Co - 14%
55Mn - 10%
57Ni - 4%

56Mn - 43%
52V - 11%
57Mn - 8%
55Cr - 7%
54Mn - 43%
52V - 11%
55Mn - 8%
55Cr - 7%
59Mn - 6%
58Mn - 15%
54V - 9%
63Co - 7%
55Cr - 6%
59Mn - 6%

0.06 s

46 s

0.5 hr

1.0 hr

2.0 hr

Si burning

O burning
Pre-supernova fluxes for at 1 kpc.

Flux at Earth (Mev$^{-1}$ s$^{-1}$ cm$^{-2}$) vs. Energy (Mev)

- 30 M$_\odot$, $\nu_e$, NH, 1 kpc
- 30 M$_\odot$, $\bar{\nu}_e$, NH, 1 kpc

- reactor $\nu$ (blue dashed line)
- solar $\nu$ (gray solid line)
- geo $\nu$ (green dotted line)

- 2 hr, 0.4 s, 0.0 s

Patton et al 2017
“A prime example is the red supergiant Betelgeuse (α Orionis) ... We find that for D=200 pc, a presupernova neutrino signal would be practically background-free — in energy windows that are realistic for detection — for several hours, and the window of observability can extend up to \( \sim 10 \) hr.”

Patton et al 2017
"A presupernova alert could be provided to the gravitational wave and electromagnetic communities..."
Identifying the Progenitor
Standard liquid scintillators could localize the pre-supernova to $\sim 70^\circ$ after $\sim 100$ detections.

Enhanced liquid scintillators could localize the pre-supernova to $\sim 15^\circ$ after $\sim 100$ detections.

Mukhopadhyay et al 2020
Probing the evolution of low mass models
The He-burning driven thermal pulses reach peaks of $L_\nu \approx 10^9 L_{\nu,\odot}$ mostly from the $^{18}\text{F}(e^+,\nu_e)^{18}\text{O}$ reaction.

Flux $\Phi_{\nu,\text{Thermal Pulse}} = 1.7 \times 10^7 (10 \text{ pc/d})^2 \text{ cm}^{-2} \text{ s}^{-1}$

timescale $\approx 0.1$ year

Average $\nu_e$ energy $\approx 0.3$ MeV

The He-flash reach peaks of $L_\nu \approx 10^4 L_{\nu,\odot}$ mostly from the same reaction.

Flux $\Phi_{\nu,\text{He flash}} = 170 (10 \text{ pc/d})^2 \text{ cm}^{-2} \text{ s}^{-1}$

timescale $\approx 3$ days

Average $\nu_e$ energy $\approx 0.3$ MeV
No good nearby targets for detections of the He-flash or thermal pulse.

After García-Sánchez et al 1999
Time for a Neutrino Cocktail