What we know and don’t know about Neutrino production in stars?

Sylvaine TURCK-CHIEZE Santa Fe June 15th 2006
Outline

– The solar neutrinos
  • The present status: what we know, what we do not know?
  • Open questions and the low energy spectrum

– The other stars toward supernovae type II
  • What we know and do not know?
  • Open questions: Toward a better determination of the presupernovae

– What are the directions for neutrino physics
  Neutrino properties **and** Neutrino astronomy
  The motivations to improve the detections …
Neutrino productions in stars

Production of neutrino fluxes

- Reaction rates (NP)
- Number of interacting species (A)
- Profile of temperature and density in the region where neutrinos are emitted (A)

For comparison with detections

- Cross sections neutrinos - detectors (NP-PP)
- Profiles of electron and neutron densities for determining oscillation parameters (A)
The Solar Neutrinos

4p $\rightarrow ^{4}\text{He} + 2e^+ + 2 \nu_e + E$

pp chain

CNO cycle

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What we know?

- **Laboratory cross sections** \(^{(3}\text{He}, \; ^{3}\text{He}; \; ^{12}\text{C}, \; p)}\)

- **Opacity calculations**

- **Acoustic modes**\(\Rightarrow\)

**Sound speed profile:** photospheric \(^{4}\text{He}\), pp reaction rate, energy transfer

- **Seismic model**

  compatible with observed sound speed for determining neutrino fluxes compatible with acoustic modes

\textit{Turck-Chièze et al. 2001; Couvidat et al. 2003}
# Direct comparison for $^8$B neutrinos

Great sensitivity to the temperature so to the detailed physics

<table>
<thead>
<tr>
<th>Flux</th>
<th>$T_c$</th>
<th>$Y_{\text{initial}}$</th>
<th>Problem solved</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>3.8 ± 1.1</td>
<td>15.6</td>
<td>SM 0.276 CNO opacity, 7Be(p,g)</td>
</tr>
<tr>
<td>1993</td>
<td>4.4 ± 1.1</td>
<td>15.43</td>
<td>SM 0.271 Fe opacity, screening</td>
</tr>
<tr>
<td>1998</td>
<td>4.82</td>
<td>15.67</td>
<td>SM 0.273 Microscopic diffusion</td>
</tr>
<tr>
<td>1999</td>
<td>4.82</td>
<td>15.71</td>
<td>SM 0.272 Turbulence in tachocline</td>
</tr>
<tr>
<td>2001</td>
<td>4.98 ± 0.73</td>
<td>15.74</td>
<td>SM 0.276 Seismic model</td>
</tr>
<tr>
<td>2003</td>
<td>5.07 ± 0.76</td>
<td>15.75</td>
<td>SM 0.277 Seismic model + magnetic field</td>
</tr>
<tr>
<td>2004</td>
<td>3.98 ± 1.1</td>
<td>15.54</td>
<td>SM 0.262 - 30% in CNO composition</td>
</tr>
<tr>
<td>2004</td>
<td>5.31 ± 0.6</td>
<td>15.75</td>
<td>SM 0.277 Seismic model + magnetic field + updated ingredients</td>
</tr>
</tbody>
</table>

SNO results
- $5.44 ± 0.99$ (CC+ES 2001)
- $5.09 ± 0.44 ± 0.45$ (NC 2002) $5.27 ± 0.27 ± 0.38$ (2003)
- $4.94 ± 0.06 ± 0.34$ active neutrinos

Aharmim et al, 2005
**Prediction for the other detectors without or with Neutrino Oscillation parameters**

<table>
<thead>
<tr>
<th>Chlorine detector</th>
<th>Seismic model 2001</th>
<th>Detected neutrinos</th>
<th>Detect. Seismic 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>pep</td>
<td>0.228</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>$^7\text{Be}$</td>
<td>1.155</td>
<td>0.66</td>
<td>0.66</td>
</tr>
<tr>
<td>$^8\text{B}$</td>
<td>5.676</td>
<td>1.76</td>
<td>1.88</td>
</tr>
<tr>
<td>$^{13}\text{N}$</td>
<td>0.096</td>
<td>0.054</td>
<td>0.022</td>
</tr>
<tr>
<td>$^{15}\text{O}$</td>
<td>0.328</td>
<td>0.187</td>
<td>0.112</td>
</tr>
<tr>
<td>total</td>
<td>7.44 SNU (1.1)</td>
<td>2.79 SNU (0.36)</td>
<td>2.76 (0.4) SNU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measurement 2.56 (0.23) SNU</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gallium detector</th>
<th>Seismic model</th>
<th>Detected neutrinos</th>
<th>Detect. Seismic 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>69.4</td>
<td>39.6</td>
<td>39.6</td>
</tr>
<tr>
<td>pep</td>
<td>2.84</td>
<td>1.62</td>
<td>1.62</td>
</tr>
<tr>
<td>$^7\text{Be}$</td>
<td>34.79</td>
<td>19.83</td>
<td>19.83</td>
</tr>
<tr>
<td>$^8\text{B}$</td>
<td>11.95</td>
<td>3.70</td>
<td>3.95</td>
</tr>
<tr>
<td>$^{13}\text{N}$</td>
<td>3.48</td>
<td>1.98</td>
<td>0.79</td>
</tr>
<tr>
<td>$^{15}\text{O}$</td>
<td>5.648</td>
<td>3.22</td>
<td>1.29</td>
</tr>
<tr>
<td>total</td>
<td>128.2 SNU (8)</td>
<td>69.95 SNU</td>
<td>67.08 (4.4) SNU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measurement 68.1 SNU (3.75)</td>
<td></td>
</tr>
</tbody>
</table>

**LMA solution** $\Delta m^2 = 7 \times 10^{-5} \text{ eV}^2 (8+0.6-0.4) \tan^2 \theta_{12} = 0.45$ BPG2003
What we don’t know?

On the astrophysics part
- CNO abundances ?? 30% uncertainty, opacities
- Internal dynamical phenomena

On the neutrino part
- agreement with chlorine experiment is not complete
- Comparison of mean values, fluctuations variation with time?
- Subleading properties: sterile neutrino, magnetic moment ?
<table>
<thead>
<tr>
<th>Topic</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same range of energy</td>
<td>99% of energy is transported by neutrinos but the explosion is not yet well understood</td>
</tr>
<tr>
<td>Role of the asymmetric explosion and of acoustic instabilities</td>
<td>New neutrino properties</td>
</tr>
<tr>
<td>Role of the dynamical effects of the progenitors</td>
<td>What don’t we know yet properly: role of rotation and magnetic field?</td>
</tr>
</tbody>
</table>
A more complete description of the Sun and stars

After the verification of the great time scales dominated by the nuclear processes, we are looking to the small time scales dominated by turbulence, convection, rotation and magnetic field.
More and more evidence that the 11 year magnetic solar cycle has an internal origin

Howe et al. 2000
The tachocline plays an important role in the stockage and amplification of the toroidal magnetic field for the Schwabe cycle 22 ans, one would like to know what phenomena can justify the possible existence of the Gleissberg cycle (90 year ?) or greater cycles ??

Development of 3D MHD simulations to understand the internal observations
Understanding the dynamics of the stars
On all scales

Asteroseismology/Magnetism

Corot/Espadon/XMM


Massive Stars
Sun
Evolved Stars
Young stars
HR stars
Transport processes in radiation zones

**Meridional circulation** (diff. rot. and A. M. transport) (ADVECTION)

**Turbulence** (shear of the diff. rot.) (DIFFUSION)

**Magnetic field**

**Internal waves**

**Secular torque**
(Charbonneau & Mac Gregor 1993, Garaud 2002)

**Instabilities**

excited at the borders with C. Z.

propagating inside R. Z.

A. M. settled where they are damped
(Goldreich & Nicholson 1989)
Sound speed down to the core
Rotation down to the limit of the nuclear core: 0.2 $R_\odot$
Dynamics of the convective zone

Rotation down to the core,
Influence of internal magnetic field
Dynamics of the radiative zone

Sylvaine Turck-Chièze, Vienna 3 April 2006
Gravity modes with SoHO

They are very informative on the core dynamics but their surface velocity is small...

GOLF spectrum:

Lifetime of the modes: hyperfine structure, complex patterns ??
Two complementary searches

- Individual modes: 150-450 $\mu$Hz
- Research of multiplets for $l=2,3$ and follow the patterns with time
  $l = 2$ ? \textit{Cox & Guzik 2004}

- Global gravity mode asymptotic behaviour $<150$ $\mu$Hz : 20-150 $\mu$Hz
- $l = 1$ \textit{Garcia, T-C et al. 2006}

Two independent methods lead to signals at the waited place with less than 2-8\% to be pure noise


\textit{Garcia et al. 2005}

4.5 sigma

\textit{Sylvaine Turck-Chièze, Vienna 3 April 2006}
Rotation profile constructed with GOLF+MDI / SOHO acoustic modes and gravity modes

What we would like to know ?

- The latitudinal rotation of the inner radiative zone
- Is there a relic of the formation of the solar system which justifies an higher central rotation profile ?
- Could we get real constraints on the magnetic configurations in the radiative zone and convective zone
- Is there a dynamo in the core ?…
A new vision of Sun and stars

1D and 3D modelling

where 4 structure equations will be replaced by 16 equations
Solar and stellar Perspectives

We are preparing a new step in solar (stellar) modelling where effects of rotation and magnetic fields will be introduced.

Space Projects PICARD 2008 then DynaMICS to study the real influence of the Sun on the Earth

COROT launch October 2006, development of asteroseismology,
Then KEPLER
Solar(stellar) neutrino Perspectives

- This step opens the route to new neutrino properties that we need to search
  - Is there central temperature fluctuations? SNO has a great sensitivity to tell us something
  - Can we separate the different neutrino sources at low energy
  - BOREXINO results
  - We would like to put constraints on
    - CNO central compositions
    - RSFP, sterile neutrinos
    - spatial scales of hundred kms as gravity modes spatial scales of thousand kms

Can we establish definitively if there is time variations of low energy solar neutrinos? ???
Solar(stellar) neutrino Perspectives

- We have still a lot of questions without answers

- We need to continue to detect solar neutrinos down to the lower energy that we can

- We need also to develop the capability of detecting supernovae detection which is the natural successor of such field with even more exciting physics