SOLAR NEUTRINOS AND HELIOSEISMOLOGY

Bases of the stellar evolution concepts: 1\textsuperscript{st} part of the XX century
Role of B. Pontecorvo 1957, 1967: Majorana? Flavour, Oscillations

1962: 1\textsuperscript{st} seismic observations –1970: understood 1995 space helioseismology
1968: 1\textsuperscript{st} solar neutrinos by Homestake then Gallex, Sage, SK,SNO, Borexino…
1970-2000: Improvements of the physics of the SSM
1995: Launch of SoHO which continues to observe the Sun (18 yrs!) up to 2016
2001-2011: Confrontation Seismic results- SNO neutrinos: role of SSeM
2008: Space asteroseismology: generalization to other stars
2010-…Building of the dynamical solar model DSM
2013-… Solar neutrinos detection for solar and stellar Physics
2013-… New neutrino properties from this field ???…..

Sylvaine Turck-Chièze  sylvaine.turck-chieze@cea.fr  Lomonosov August 23th 2013
- The joined effort from Solar Standard Model, neutrino detections and seismology: results, accuracy, questions

- The development of precise neutrino detections, laser facilities and accelerators to build the DSM: Dynamical Solar Model
Review papers

  Revisiting the standard solar model

  The solar interior

  Solar neutrinos, helioseismology and the solar internal dynamics

  Solar and stellar astrophysics and dark matter
Hypotheses, building and accuracy of the SSM

**TABLE 8**

**NEUTRINO CAPTURE RATES AND UNCERTAINTIES**

<table>
<thead>
<tr>
<th>Uncertainties Sources ($p_j$)</th>
<th>Uncertainty (1 $\sigma$ error)</th>
<th>$\frac{\partial \ln \phi_{pp}}{\partial p_j}$</th>
<th>$\frac{\partial \ln \phi_{8B}}{\partial p_j}$</th>
<th>$^{71}$Ga Detector</th>
<th>$^{37}$Cl Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>($p, p$) reaction</td>
<td>2%</td>
<td>0.14</td>
<td>-2.7</td>
<td>1.8%</td>
<td>3.9%</td>
</tr>
<tr>
<td>($^3$He, $^3$He) reaction</td>
<td>5%</td>
<td>0.03</td>
<td>0.42</td>
<td>$\leq 0.1%$</td>
<td>1.6%</td>
</tr>
<tr>
<td>($^3$He, $^4$He) reaction</td>
<td>4%</td>
<td>-0.06</td>
<td>0.83</td>
<td>1%</td>
<td>2.7%</td>
</tr>
<tr>
<td>($^7$Be, $p$) reaction</td>
<td>15%</td>
<td>0</td>
<td>1</td>
<td>1%</td>
<td>15%</td>
</tr>
<tr>
<td>$L_0$</td>
<td>0.5%</td>
<td>0.69</td>
<td>7.2</td>
<td>0.3%</td>
<td>3.6%</td>
</tr>
<tr>
<td>$Z/X$</td>
<td>10%</td>
<td>-0.05</td>
<td>1.26</td>
<td>1.8%</td>
<td>9%</td>
</tr>
<tr>
<td>Age</td>
<td>2%</td>
<td>-0.07</td>
<td>1.4</td>
<td>$\leq 1%$</td>
<td>2%</td>
</tr>
<tr>
<td>Opacity:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T \leq 5 \times 10^5$ K</td>
<td>$\geq 10%$</td>
<td>0.02</td>
<td>0.13</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>$\geq 5 \times 10^5$ K</td>
<td>5%</td>
<td>-0.012</td>
<td>2.6</td>
<td>$\leq 1%$</td>
<td>12%</td>
</tr>
<tr>
<td>$\sigma_{abs}$</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>2.5%</td>
<td>4%</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td></td>
<td></td>
<td></td>
<td>4.2%</td>
<td>22%</td>
</tr>
</tbody>
</table>

No oscillation of neutrinos

B. Pontecorvo waiting the first gallium results in 1992: small uncertainty as pp flux is directly connected to the solar luminosity
Are the hypotheses of the SSM correct??

Table 6. Evolution with time of the SSM or seismic predictions of the $^8$B neutrino flux in $10^6$ cm$^{-2}$ s$^{-1}$. Added are the central temperature $T_C$ in $10^6$ K, the initial helium abundance $Y$ in mass fraction and a specific problem that was solved. From Turck-Chièze et al (2010a).

<table>
<thead>
<tr>
<th>$^8$B flux</th>
<th>$T_C$</th>
<th>$Y_{initial}$</th>
<th>Problem solved</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8 ± 1.1</td>
<td>15.6</td>
<td>0.276</td>
<td>CNO opacity, $^7$Be(p, γ)</td>
<td>Turck-Chièze et al (1988)</td>
</tr>
<tr>
<td>4.4 ± 1.1</td>
<td>15.43</td>
<td>0.271</td>
<td>−30% Fe abundance, screening</td>
<td>Turck-Chièze and Lopes (1993)</td>
</tr>
<tr>
<td>4.82</td>
<td>15.67</td>
<td>0.273</td>
<td>Microscopic diffusion</td>
<td>Brun et al (1998)</td>
</tr>
<tr>
<td>4.82</td>
<td>15.71</td>
<td>0.272</td>
<td>Turbulence tachocline</td>
<td>Brun et al (1999)</td>
</tr>
<tr>
<td>4.98 ± 0.73</td>
<td>15.74</td>
<td>0.276</td>
<td>Seismic model</td>
<td>Turck-Chièze et al (2001b)</td>
</tr>
<tr>
<td>5.07 ± 0.76</td>
<td>15.75</td>
<td>0.277</td>
<td>Seismic model, magnetic field</td>
<td>Couvidat et al (2003)</td>
</tr>
<tr>
<td>3.98 ± 1.1</td>
<td>15.54</td>
<td>0.262</td>
<td>−30% CNO composition</td>
<td>Turck-Chièze et al (2004a)</td>
</tr>
<tr>
<td>5.31 ± 0.6</td>
<td>15.75</td>
<td>0.277</td>
<td>Seismic model + $^7$Be and $^{14}$N(p, γ)</td>
<td>Turck-Chièze et al (2004b)</td>
</tr>
<tr>
<td>4.21 ± 1.2</td>
<td>15.51</td>
<td>0.262</td>
<td>SSM (Asplund 2009)</td>
<td>Turck-Chièze et al (2010a, 2010b)</td>
</tr>
</tbody>
</table>

SNO + Super Kamiokande: $5.27 ± 0.27 ±0.38 \times 10^6$ cm$^{-2}$ s$^{-1}$
Neutrino predictions depend on the state of art of the microscopic physics of the SSM.
The joined effort from neutrino detections and seismology: results, accuracy, questions
Sun: globally and locally => millions of modes

Other stars : globally only about one hundred modes

Methods:
- variability of the radial velocity: SoHO, SDO and ground asteroseismology
- variability of the stellar photometry: COROT, KEPLER, PICARD

Photospheric helium: 0.25 in mass fraction which checks the microscopic diffusion for that element and BZC: 0.7 f^2 R_{\odot}
The performances of GOLF allow to detect low frequency acoustic modes that penetrate in the core and first gravity modes by contrast to high frequency acoustic modes that are sensitive to the solar activity.
The modes are characterized by 3 numbers: degree \(l\), order \(n\), azimutal order \(m\):
degeneracy of the mode in \(2l+1\) components:
Information on rotation and magnetic field

Ulrich 1971, Leibacher & Stein 1972

Acoustic frequencies \((l,n)\) allow to extract the solar sound speed and density

\[
\frac{\delta \omega_{nl}}{\omega_{nl}} = \int_0^R \left[ K_c^{(nl)}(r) \frac{\delta c}{c} (r) + K_\rho^{(nl)}(r) \frac{\delta \rho}{\rho} (r) \right] dr + Q_{nl}^{-1} G(\omega_{nl})
\]

Gravity and acoustic modes splittings \((m)\) allow also to extract solar rotation and magnetic field

\[
\delta \omega_{nlm} = m \int_0^R \int_0^{\pi} K_{nlm}(r,\theta)\Omega(r,\vartheta) r dr d\theta
\]
The sound speed profile is strongly sensitive to main reaction rates

Turck-Chièze, Piau, Couvidat ApJ lett. 2010

Accuracy sound speed: $3 \times 10^{-4}$ at $0.08 \ R_\odot$

See all the values in T-C et al. 2001
Turck-Chièze & Lopes 2012 RAA
The seismic results have allowed to check the maxwellian distribution of reactant velocities

\[ r_{12} \sim \int S(E) \exp\left(\frac{-E}{kT} - b/\sqrt{E}\right) dE, \]

\[ (r_{12})_\delta = r_{12} F_{\text{corr}}(\delta). \]

\[ E_0 = \left[ \frac{b kT}{2} \right]^{2/3} \quad E_0 = 1.220 (Z_1^2 Z_2^2 A T_6^2)^{1/3} \text{ keV} \]

Since 2001, SSem uses the sound speed profile from surface down to the core to stabilize the neutrino predictions contrary to SSM.

The differences between SSM with Asplund et al. composition (2009), the reduction with new CNO composition and observations appear in red.

These differences are extremely large in comparison with the observed error bars problem in the thermodynamic physics of the internal Sun? Or in Dynamics?

- A seismic solar model has been built in black for a better prediction of observables
  
  Interest for fundamental physics


Dependence of the thermodynamical quantities to the solar photospheric composition

Helioseismology and neutrinos agree today through SSeM

The agreement with SSM predictions is not so good including new $^{14}\text{N}(p, \gamma)$ estimate and new CNO photospheric abundances

<table>
<thead>
<tr>
<th></th>
<th>Predictions without neutrino oscillation</th>
<th>Predictions with neutrino oscillation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HOMESTAKE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard model 2009</td>
<td>6.315 SNU</td>
<td>2.24 SNU</td>
</tr>
<tr>
<td>Seismic model</td>
<td>7.67 ± 1.1 SNU</td>
<td>2.76 ± 0.4 SNU</td>
</tr>
<tr>
<td><strong>GALLIUM detectors</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GALLEX</td>
<td>73.4 ± 7.2 SNU</td>
<td></td>
</tr>
<tr>
<td>GNO</td>
<td>62.9 ± 5.4 ± 2.5 SNU</td>
<td></td>
</tr>
<tr>
<td>GALLEX + GNO</td>
<td>67.6 ± 3.2 SNU</td>
<td></td>
</tr>
<tr>
<td>SAGE</td>
<td>65.4 ± 3.3 ± 2.7 SNU</td>
<td></td>
</tr>
<tr>
<td>GALLEX+GNO+SAGE</td>
<td>66.1 ± 3. SNU</td>
<td></td>
</tr>
<tr>
<td>Standard model 2009</td>
<td>120.9 SNU</td>
<td>64.1 SNU</td>
</tr>
<tr>
<td>Seismic model</td>
<td>123.4 ± 8.2 SNU</td>
<td>67.1 ± 4.4 SNU</td>
</tr>
<tr>
<td><strong>BOREXINO $^{7}\text{Be}$</strong></td>
<td></td>
<td>3.36 ± 0.36 $10^9 \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>Standard model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seismic model</td>
<td>4.72 $10^9 \text{cm}^{-2}\text{s}^{-1}$</td>
<td>3.045 ± 0.35 $10^9 \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Water detectors</strong></th>
<th>Predictions or Detectors $B^8$ electronic neutrino flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNO</td>
<td>5.045 ± 0.13 (stat) ± 0.13 (syst) $10^6 \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>SNO +SK</td>
<td>5.27 ± 0.27 (stat) ± 0.38 (syst) $10^6 \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>Standard model 2009</td>
<td>4.21 ± 1.2 $10^6 \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>Seismic model</td>
<td>5.31 ± 0.6 $10^6 \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
</tbody>
</table>

$B^8$ neutrino flux electronic + other flavors in $10^6 \text{cm}^{-2}\text{s}^{-1}$
WIMPs properties from the knowledge of the solar core


• The core of the Sun is now well constrained by SNO+SK neutrinos detection: constraints on the central temperature and gravity modes: constraints on the central density through the seismic model that predicts correctly both detections:

• $T_c = 15.74 \times 10^6 K$

• $\rho_c = 153.6 \text{ g/cm}^3$

• This fact puts some constraints on the mass of WIMPs, first candidates for dark matter if one considers realistic spin dependent and independent cross sections:

For $\Sigma_{\text{ann}}$ of $10^{-50} \text{ cm}^2$, $\sigma_{\text{SD}} = 7$ to $5 \times 10^{-36} \text{ cm}^2$

$\sigma_{\text{SI}} = 10^{-40} \text{ cm}^2$  $M_{\text{WIMPS}} < 12 \text{ GeV}$ are rejected

We see no signature of WIMPs from observations of the Solar Core
Future solar neutrino observations

Precise neutrino measurements: 1 to 5%

to build the
Dynamical Solar Model
2004-2013: Extraction of the rotation profile from the surface to the core thanks to acoustic and gravity modes and of the magnetic field just near the surface

The GOLF instrument has determined a first insight on the core solar rotation. It rotates about 6-8 times greater than the rest of the radiative zone. This is probably a relic of the initial contracting phase, so some insight on the solar system formation. At that period, a dynamo could have been created in the solar central region: impact of our Sun on young planets, which may help to explain a believed warm young Mars.

The observed 11 and 2 year helioseismic periodicities are connected to the subsurface magnetic field. No direct magnetic field estimate of the solar interior is given by helioseismology up to now.

Solar Neutrino Astrophysics

• Production of energy: pp and pep fluxes
• CNO fluxes: CNO abundance and screening in the core
• Electronic density
• Time variability of neutrino fluxes due to gravity modes or gravity waves
The energetic balance of Sun and stars in SSM

Are stellar structure equations enough?
Other stars, formation of planets, present Sun-Earth relationship

Transformation of produced energy, transport of energy, transport of angular momentum

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Check the energetic balance and the electronic density profile


- $T_c$ seismic model $15.74 \times 10^6$ K
- $T_c$ SSM $15.54 \times 10^6$ K

- $\rho_c$ seismic model $153.02$ g/cm$^3$
- $\rho_c$ SSM $150.06$ g/cm$^3$

- $X_c$ seismic model $0.339$
- $Y_{\text{initial}}$ $0.277$, $Y_{\text{surf}}$ $0.251$

- 1.5% difference in central temperature $\Rightarrow$ no more than 5-6% difference in luminosity $L_{\text{nuc}} > L_{\text{sol}}$

Redistribution in kinetic energy, magnetic energy, meridional motions, energy of the gravity waves

Another part through transfer of energy by photons.

- Core CNO given by $N^{15}$ and $0^{15}\nu$ fluxes
- Spectroscopy of neutrinos gives access to the electronic density profile.
Time variability in the RZ
Can we see the generated gravity waves through time variability of the $^8$B neutrino flux or other neutrino fluxes: periods of hours?

Basu & Antia 2003
Macroscopic effect on microscopic physics

Prediction of two different meridional circulation velocity in RZ and CZ
Brun, T-C, Zahn 1999, Turck-Chièze, Palacios, Marques et al. 2010

\[ v \approx 10^{-6} \text{ to } 10^{-7} \text{ cm/s in RZ compared to several cm/s in CZ} \]

We need to calculate the impact of the tachocline shear on the microscopic diffusion of the Sun: 10% or more impact of CNO, Si, Fe in the core!! Can we constrain the CNO abundance in the core by neutrinos?...
We develop a program to reestimate opacity calculations and measure opacities and reaction rates in plasmas generated by HE lasers like LMJ (Bordeaux, France).

Production of equivalent $T$ and $\rho$ than center of the Sun during some ps

Program for the next decade: $d+p \rightarrow ^3$He +$\gamma$; $d+d \rightarrow ^3$He+n; $p+^7$Li; $p+^{11}$B$\rightarrow$ $3 \alpha$ ....
How we shall progress?

We are preparing new calculations for stellar physics and we begin to understand the differences with OPAL.

New experiments on laser facilities: ORION, LMJ

New interpolations with OPAS calculations of opacity

Turck-Chièze et al. HEDP 2009, 2013
Summary

SSM is today checked and compared to two kinds of observations: neutrinos & seismology. Its quality is clearly reasonable: 1% for central temperature, 1% for radial sound speed.

Observed differences between SSM and the Sun are significant: We can learn more on microscopic and dynamical Physics of the solar core.

Accurate neutrino flux predictions still depend on crucial nuclear reaction rates, their screening effects, and the abundance of pp and CNO elements.

Precise neutrino astronomy is coming:
- CNO neutrino for CNO abundance and screening,
- pep or pp neutrino flux for energetic balance,
- $^8$B and $^7$Be neutrino fluxes for electronic density, time gravity waves variability.

In parallel and independently, large laser facilities are promising to check the screening effects and the transfer of radiation in plasmas => Dynamical model of the Sun.

May be these new developments can also improve our knowledge of neutrinos, like in the past.
Main collaborators

- C. Blancard, S. Brun, T. Caillaud, P. Cosse, S. Couvidat (Stanford),
- T. Blenski, J. E. Ducret, H. Dzitko,
  J. Farriaut, G. Faussurier, R. Garcia, D. Gilles,
  F. Gilleron, M. LePennec, G. Loisel, I. Lopes, S. Mathis,
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- S. Bastiani  Ecole Polytechnique France
- M. Busquet, ARTEP, USA
- J. Colgan, D.P. Kilcrease, N.H. Magee Los Alamos, USA
- J. W. Harris from AWE England
Screening factor?

Dzitko, T-C et al. 1995,
Gruzinov & Bahcall 1998

This effect has never been measured before

\[ f = \log \Lambda \text{ where } \Lambda = U(0)/kT \]
Helium content and base of the convective zone

\[ c^2 = \Gamma_1 \frac{P}{\rho} \propto \frac{T}{\mu} \]

Photospheric helium: 0.25 in mass fraction which checks the microscopic diffusion for that element and BZC: 0.713 \( R_{\text{sol}} \)