How helioseismology constrains solar neutrino properties?

- The Sun, different sources of neutrinos
- A new picture of the Sun
- Perspectives for the Sun, other stars links between astrophysics and particle physics

Sylvaine Turck-Chièze, SAp/DAPNIA/CEA
A special case: The Sun as a laboratory, for physics and astrophysics

Knowing the source $\iff$ Neutrino properties

Theoretical progress

Seismic investigation

Neutrino detections

sound speed
internal rotation
magnetic field
The production of the solar neutrino fluxes
from theory to observational determination
Improvements on classical physical phenomena 1988-2001

- no mixing in the core Sol. Phys. 2001
- support for a mawxellian distribution for the particle velocities Sol. Phys 2001

Improvements of solar models constrained by seismology


Sylvaine Turck-Chièze Neutrino 2004
22 SNU

Predicted $^{37}\text{Cl}$ Rate vs. Time

Bahcall and collaborators

Turck-Chièze and collaborators

Progress drained by helioseismology

Year of Publication
### $^8$B neutrino flux in $10^6 cm^{-2}s^{-1}$, Tc in $10^6 K$

<table>
<thead>
<tr>
<th>Flux</th>
<th>Tc</th>
<th>Y initial</th>
<th>Problem solved</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>3.8 ± 1.1</td>
<td>15.6</td>
<td>0.276</td>
</tr>
<tr>
<td>1993</td>
<td>4.4 ± 1.1</td>
<td>15.43</td>
<td>0.271</td>
</tr>
<tr>
<td>1998</td>
<td>4.82</td>
<td>15.67</td>
<td>0.273</td>
</tr>
<tr>
<td>1999</td>
<td>4.82</td>
<td>15.71</td>
<td>0.272</td>
</tr>
<tr>
<td>2001</td>
<td>4.98 ± 0.73</td>
<td>15.74</td>
<td>0.276</td>
</tr>
<tr>
<td>2003</td>
<td>5.07 ±0.76</td>
<td>15.75</td>
<td>0.277</td>
</tr>
<tr>
<td>2004</td>
<td>3.98. ± 1.1</td>
<td>15.54</td>
<td>0.262</td>
</tr>
</tbody>
</table>

**Problem solved**
- CNO opacity, $^7$Be(p,g) (1988)
- Fe opacity, screening (1993)
- Microscopic diffusion (1998)
- Turbulence in tachocline (1999)
- Seismic model (2001)
- Seismic model + magnetic field (2003)
- 30% in CNO composition (2004)

**SNO results**
- $5.44 ± 0.99$ (CC+ES 2001)
- $5.09 ±0.44 ±0.45$ (NC 2002)
- $5.27 ±0.27 ±0.38$ (2003)

In grey pure theoretical models with improved physics, in red models which fit seismic observations.
GOLF/SoHO experiment

Gabriel, Turck-Chièze, Roca-Cortes, Grec, Robillot

a french-spanish collaboration

\[ n > 15, \text{1 year} \]

\[ n > 15, \text{5 years} \]

\[ n < 16 \text{ no problem of stochastic excitation} \]

\[ 0.4 \, \mu \text{Hz} \]

Sylvaine Turck-Chièze Neutrino 2004
The Seismic model: GOLF+ MDI includes the best physics and an adjustment to reproduce the seismic results.


very good constrain on the central temperature

Solar composition in C, N, O recently reduced by 30%

The Sun is no more an « enriched » star in heavy elements; a new problem solved.

\[ {^8}\text{B neutrino flux} = 4 \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \]
\[ {^8}\text{B seismic model} = 5 \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \]
• It is better to compare neutrino results to seismic models than to « standard models »!

• Do not hesitate to quote seismic data and models constrained by in situ observations

• Progress toward a coherent and complete picture of the Sun useful for progressing in Astrophysics and Particle physics
Oscillation parameters

$$\Delta m^2 = 7 \times 10^{-5} \text{ eV}^2 \quad \text{tg}^2 \theta_{12} = 0.45 \quad \text{BPG2003}$$

<table>
<thead>
<tr>
<th>Chlorine experiment</th>
<th>Seismic model</th>
<th>Detected neutrinos</th>
</tr>
</thead>
<tbody>
<tr>
<td>pep</td>
<td>0.228</td>
<td>0.13</td>
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<tr>
<td>$^7\text{Be}$</td>
<td>1.155</td>
<td>57%</td>
</tr>
<tr>
<td>$^8\text{B}$</td>
<td>5.676</td>
<td>31%</td>
</tr>
<tr>
<td>$^{13}\text{N}$</td>
<td>0.096</td>
<td>57%</td>
</tr>
<tr>
<td>$^{15}\text{O}$</td>
<td>0.328</td>
<td>57%</td>
</tr>
<tr>
<td>total</td>
<td>7.44 SNU (0.96)</td>
<td>2.79 SNU (0.36)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gallium experiment</th>
<th>Seismic model</th>
<th>Detected neutrinos</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>69.4</td>
<td>39.6</td>
</tr>
<tr>
<td>pep</td>
<td>2.84</td>
<td>1.62</td>
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<tr>
<td>$^7\text{Be}$</td>
<td>34.79</td>
<td>19.83</td>
</tr>
<tr>
<td>$^8\text{B}$</td>
<td>11.95</td>
<td>3.70</td>
</tr>
<tr>
<td>$^{13}\text{N}$</td>
<td>3.48</td>
<td>1.98</td>
</tr>
<tr>
<td>$^{15}\text{O}$</td>
<td>5.648</td>
<td>3.22</td>
</tr>
<tr>
<td>total</td>
<td>128.2 SNU (7)</td>
<td>69.95 SNU</td>
</tr>
</tbody>
</table>

Interest of low energy experiments: Borexino, Lens to verify, some discrepancy?...
Already beautiful constraints on pp and CNO chains


-65% CNO
Cl: 6.1 SNU
Ga: 121SNU

8B: $3.81 \times 10^6$
not compatible with SNO

The Sun energy production is under control thanks to helioseismology + SNO results!

pp: -5% for check of screening or Maxwell distribution

Sylvaine Turck
A new vision of the Sun

The Sun is a magnetic Sun
the Sun is not standard !!!
Magnetic Solar Cycle 23 (EIT, LASCO & MDI Data)

Source: NASA
Theoretical Solar Cycle: Internal origin

we need to understand the role of the rotation to estimate the magnetic field
First step: the rotation profile GOLF + MDI

Progress in radiative zone
Magnetohydrodynamical 3D calculations

Mean Angular Velocity $\Omega$


At the equator the flow is poleward

Fast equator

Slow poles

GONG DATA

SIMULATION

Associated Meridional Circulation

Multi cells flow
Mean Angular Velocity $\Omega$

Initial state of differential rotation

Evolved state of differential rotation under the influence of the Lorentz force

The important role of the magnetic field in the radiative zone

MHD simulation Brun et al.

Rudiger & Kitchatinov 1997
Mc Gregor & Charbonneau 1999
tachocline
B_\phi = 2 \times 10^6 B_0^{1/3}
B_0 \sim 2 \times 10^{-4} G,
B_\phi \sim 10^5 G
Magnetic field in the Sun and Neutrino Properties

\[ B = 10 \text{ kG at } 0.995 \]
\[ \Delta B = 100 \text{G along the cycle} \]
\[ \text{Nghiem et al, 2004} \]


External zone, flux tube, \( B = 4000 \text{G} \)
Tachocline \( B < 300 \text{kG}, m_v > 3 \times 10^{-12} \mu \text{B} \)
Radiative zone: \( B < 30 \text{MG}, m_v > 5 \times 10^{-15} \mu \text{B} \)
limit of 7 MG ? from deformed Sun

\[ \text{Couvidat, T-C, Kosovichev 2003} \]
Perspectives

Sun, other stars,
new links between Astrophysics and
Particle Physics
A better insight on the radiative region and solar core

Gravity Modes

$l=1 \quad n=1 \text{ à } 6$

It contains 98% of the solar mass

Improvements on the spatial resolution, density, rotation and central magnetic field
A new project to progress on gravity modes


gravity modes candidates (2004)

800 days

1700 days

2100 days
New analysis after 3000 days

SoHO gain

Acoustic modes

Gravity modes

l=1, n=1

gravity mode

l=5?

velocity down to 2mm/s
Decrease of the solar noise due to granulation by a factor 5 to 10

Decrease of the statistical error by a factor 5 to 10
GOLF-NG: Scientific objectives

GOLF-NG: Solar study of the temporal variability of internal processes, improvement of the solar core knowledge, progress on internal magnetic field

- Deep understanding of the Sun as a magnetic star
- Relation Sun-Earth: long variability, climate, cycles

Constraints on dark matter

- Microsatellite CNES 2008-2009 ? in parallel and (or) complement to SDO/
- then 2010-2012 sentinel ILWS ??

- Successor of GOLF
- Prototype phase on ground
- Measurements in Canaries Teide, Summer 2005

Measurement of lower velocities in understanding better the sodium line and in measuring quicker to get the temporal variations
We know already from GOLF
On ground Prototype GOLF-NG 1999-2005

PI: S. Turck-Chièze

- technological validation

variable magnet from 2 to 8 kG: OK

thermic study

resonance cell

suppression of the mechanisms

photodiodes

Microsatellite project 2008?

I need your support
GOLF-NG: microsatellite version

International project CEA-France Spain

- Launch in GOLF-NG 2008-2009
- Launch of COROT 2006: asteroseismology and exoplanets
- Launch of HMI / SDO in 2008

Then if convincing other spatial projects on long missions: several years
Constant progress has been noticed on the knowledge of the Sun and solar neutrinos

We will use soon constraints coming from gravity modes

Special and competitive case to continue to learn news properties of the neutrinos: Majorana? or magnetic moment? or to put constraints on dark matter

Prepare next generation of neutrino investigations: supernovae or high energy sources

Need of new generation of instruments on both sides mutual assistance to get these projects
Responsabilités fonctionnelles
- Responsable Scientifique : Sylvaine TURCK-CHIEZE, CEA SAp
- Responsable Instrument : Jean-Maurice ROBILLOT, Obs.de Bordeaux → R. Garcia
- Chef de Projet : Pierre-Henri CARTON, CEA SEDI

Responsabilités techniques
SEDI : - Etudes design Optique
- Etudes et réalisation Photodétecteurs, chaîne de mesure, Acquisition
- Intégration matériels et logiciels, Tests et calibration, Installation sur site

SIS : - Etudes mécano-thermiques
- Etudes Ctrl/Cde
- Conception et réalisations sous-systèmes

IAC : - Réalisation du sous-système de polarisation optique
- Réalisation des interfaces (mécaniques, DAQ, ...) liées au site d'installation

NICE : - Suivi instrumental et définition de l’analyse

Ressources humaines Saclay aujourd’hui
- 2 astrophysiciens, 3 ingénieurs, 4 techniciens + IAC: contrat 3 ans. Futur IAS ? Imagerie ?