WISP solutions to the solar abundance problem: general requirements and an example

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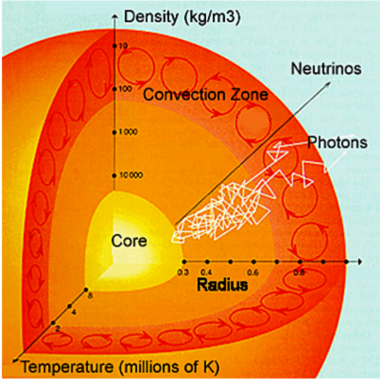
The Sun



- core
- radiation zone
- convection zone
- ✓ high temperature
- ✓ large magnetic fields

Standard solar model

input: $\tau_\odot$, $M_\odot$, $L_\odot$, $R_\odot$, $(Z/X)_\odot$, $\kappa(\rho, T, X_i)$, $\epsilon(\rho, T, X_i)$

$$
\left\{
\begin{array}{ll}
\frac{dP}{dr} = -\frac{GM\rho}{r^2}, & \triangleright \text{ hydrostatic equilibrium} \\
\frac{dM}{dr} = 4\pi r^2 \rho, & \triangleright \text{ continuity} \\
\frac{dL}{dr} = 4\pi r^2 \rho \left(\epsilon_{\text{nuc}} - \epsilon_\nu\right), & \triangleright \text{ energy production} \\
\frac{dT}{dr} = \begin{cases} -\frac{3\kappa\rho L}{64\pi r^2 \sigma T^3}, & \nabla_{rad} < \nabla_{ad} \\ \nabla_{ad} \cdot \frac{T}{P}\frac{dP}{dr}, & \nabla_{rad} \geq \nabla_{ad} \end{cases} & \triangleright \text{ energy transfer} \\
P = \frac{\rho T}{\mu m_H} & \triangleright \text{ equation of state}
\end{array}
\right.
$$

fit: Y_{ini}, Z_{ini}, α_{MLT}

output: $T(r)$, $P(r)$, $\rho(r)$, $M(r)$, $L(r)$, $X_i(r)$, $\Phi_{\nu,i}$

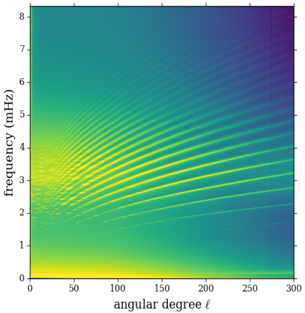
Solar physics in the XXI century

Solar physics – rapidly developing field of science

- Solar neutrinos
- Non-equilibrium 3D models of the atmosphere $\rightarrow$ chemical composition AGSS09
- Opacity function: calculations and experiment
- Helioseismology: new data

Helioseismology

Solar oscillations spectrum is used to determine:

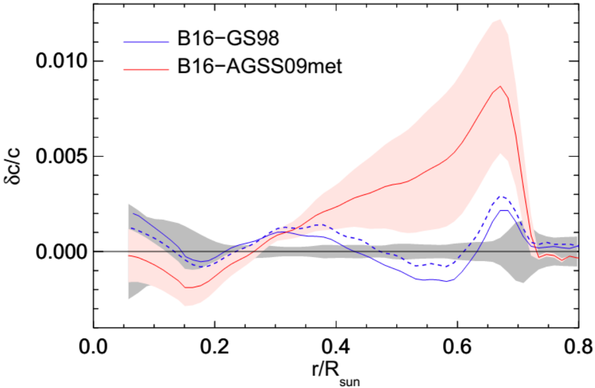


- sound speed profile
- surface helium abundance
- depth of the convection zone
- density profile
- differential rotation profile

NB! $L/M^3 \sim \mu^4/\kappa$

Solar abundance problem

Helioseismological sound speed profile does not agree with the Standard solar model calculations, significance $4.7\,\sigma$ (Vinyoles'16)



Attempts at the solution

- Opacity increase (no physical mechanism known)
- Rotation with enhanced gravitational settling (no physical mechanism known)
- Additional diffusive energy transfer in the core by DM (partial solution; required dipole moments excluded by direct search experiments)
- Accretion, 3D models, fifth force etc. – no solution

Non-diffusive energy transfer

Emission of particles and absorption of energy → varition of $\epsilon(m)$.

$$l(m) = \xi_1 \int_0^m \left(\epsilon_{\text{nuc}}(\bar{m}) - \epsilon_\nu(\bar{m}) + \sum_i \epsilon_i(\bar{m}) \right) d\bar{m}, \qquad l(1) = 1$$

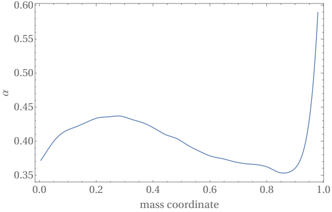
$$\sum_i \epsilon_i = \sum_i \tilde{\epsilon}_i + \bar{\epsilon}, \quad \bar{\epsilon} \equiv \int_0^1 dm \sum_i \epsilon_i$$

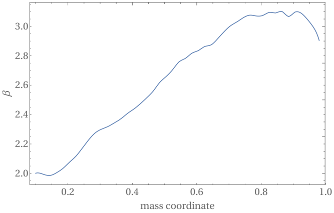
Effects:

- $\sum_i \tilde{\epsilon}_i \longrightarrow$ variation of the shape of $l(m)$
- $\bar{\epsilon} \longrightarrow$ change in nuclear reactions rates $\epsilon_{\text{nuc}} - \epsilon_\nu$

Two models: part I

- switch to the mass coordinate
- $p' \propto -m/r^4, \; t' \propto -\kappa l/(r^4 t^3) \quad \Longrightarrow \quad l \propto m\, t^3\, t'/(\kappa\, p')$
- $\kappa \propto \rho^{\alpha}\, t^{-\beta}$, OPAL tables, composition AGSS09





- two models: Standard and corrected, $\delta \equiv$ difference

$$\delta\rho/\rho, \; \delta c_s/c_s, \; \delta\mu/\mu, \; \delta t/t, \; \delta r/r, \; \delta p'/p' \ll 1$$

$$\frac{\delta l}{l} = 2\cdot(3+\beta)\,\frac{\delta c_s}{c_s} - (\alpha+1)\,\frac{\delta\rho}{\rho} + (4+\beta)\,\frac{\delta\mu}{\mu} + \frac{c_s}{c_s'}\left[\left(\frac{\delta c_s}{c_s}\right)' + \frac{1}{2}\left(\frac{\delta\mu}{\mu}\right)'\right] - \left[\frac{p}{p'}\left(\frac{\delta\rho}{\rho}\right)' + 2\,\frac{p}{p'}\left(\frac{\delta c_s}{c_s}\right)'\right]$$

Two models: part II

- two models: Standard and with increased opacity (Villante'15)
- variation of $l(m)$ now only in the core: $\bar{\delta} l(m) = \bar{\delta} l_{\rm nuc}(m)$, $\bar{\delta} l_{\rm nuc}/l_{\rm nuc} \ll 1$
- $\kappa \propto m t^3 t'/(l p') \quad \Longrightarrow$

$$\frac{\bar{\delta}\kappa}{\kappa} = 3\,\frac{\bar{\delta} t}{t} + \frac{\bar{\delta} t'}{t'} - \frac{\bar{\delta} p'}{p'} - \left(\frac{\bar{\delta} l}{l}\right)_{\rm nuc}$$

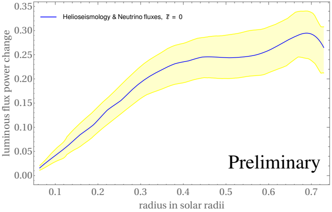
- helioseismology: $\delta c_s = \bar{\delta} c_s$ и $\delta\rho = \bar{\delta}\rho \quad \Rightarrow \quad \delta p' = \bar{\delta} p'$, as well as

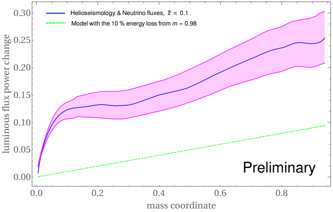
$$\frac{\delta\mu}{\mu} = \frac{\bar{\delta}\mu}{\mu} + \left(\frac{\delta\mu}{\mu}\right)_{\rm nuc}, \qquad \frac{\bar{\delta}\mu}{\mu} = \frac{5\,\delta Y_s}{8 - 5\,Y}$$

Luminous flux power profile

Inside the radiation zone and the core: $[\forall x : (x)_{\text{nuc}} \propto \bar{\epsilon}]$

$$(\delta I)_{\tilde{\epsilon}} = I \cdot \left(\frac{\bar{\delta}\kappa}{\kappa} + 2\beta \frac{\delta c_s}{c_s} - \alpha \frac{\delta\rho}{\rho} + \beta \frac{\bar{\delta}\mu}{\mu} + (4+\beta) \cdot \left(\frac{\delta\mu}{\mu}\right)_{\text{nuc}} + \frac{c_s}{2\,c_s'} \left(\frac{\delta\mu}{\mu}\right)'_{\text{nuc}} + \left(\frac{\delta I - \bar{\delta} I}{I}\right)_{\text{nuc}} \right)$$





Inside the convection zone: $\delta I = 0 \longrightarrow$ energy emission

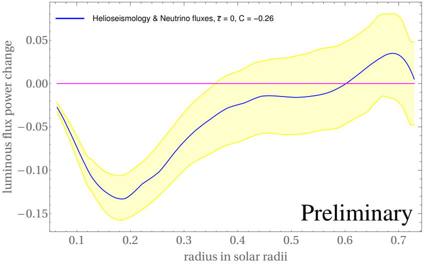
Rescaling of the opacity

Global rescaling of opacity does not influence sound speed profile:

$$\kappa \to (1+C)\cdot\kappa, \qquad r \to r \quad (R_\odot = \mathrm{const})$$

$$\int dm\, Gm/r = 2\cdot 3/2 \int PdV = 3\int dm\, P/\rho \propto \int dm\, c_s^2 \quad \Rightarrow \quad c_s \to c_s$$

Analogue of the proposed DM solutions:



Model

Consider vector extension of SM with kinetic and mass mixing:

$$L_0 = -\frac{1}{4}F_{1\mu\nu}F_1^{\mu\nu} - \frac{1}{4}F_{2\mu\nu}F_2^{\mu\nu} - \frac{\delta}{2}F_{1\mu\nu}F_2^{\mu\nu},$$

$$L_1 = J'_\mu A_1^\mu + J_\mu A_2^\mu,$$

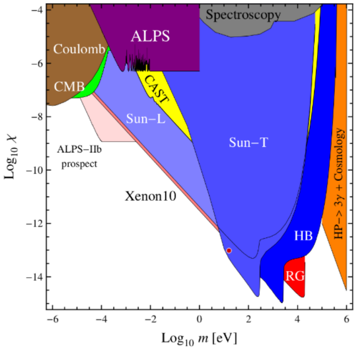
$$L_{Mass} = -\frac{1}{2}M_1^2 A_{1\mu}A_1^\mu - \frac{1}{2}M_2^2 A_{2\mu}A_2^\mu - M_1 M_2 A_{1\mu}A_2^\mu.$$

After diagonalization the interaction is:

$$L_1 = \frac{1}{\sqrt{1-2\delta\epsilon+\epsilon^2}}\left(\frac{\epsilon-\delta}{\sqrt{1-\delta^2}}J_\mu + \frac{1-\epsilon\delta}{\sqrt{1-\delta^2}}J'_\mu\right)A_M^\mu + \frac{1}{\sqrt{1-2\delta\epsilon+\epsilon^2}}\left(J_\mu - \epsilon J'_\mu\right)A_\gamma^\mu.$$

Emission of dark photons

radiation zone boundary $\to M = 12$ eV – dark photon mass



- emitting region is a sphere
- power emitted:

$$L_{\gamma'} = 0.26 \cdot \left(\frac{\delta}{1.5 \cdot 10^{-13}} \right)^2$$

- beyond constraints (Redondo'13)

$M \gg m_c \quad \to \quad$ decay to millicharges

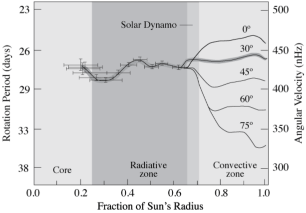
Capture inside the Sun

- capture due to millicharge $\varepsilon \equiv \epsilon\, e'/e$:

$$r_L = \frac{\sqrt{\omega_c^2 - m_c^2}}{\epsilon e' B} = 0.01\, R_\odot \cdot \left(\frac{\omega_c}{\mathrm{keV}}\right) \left(\frac{B}{0.7\,\mathrm{MG}}\right)^{-1} \left(\frac{\varepsilon}{7 \cdot 10^{-15}}\right)^{-1}$$

- Ferraro law and helioseismology $\rightarrow$ magnetic field confinement (Lang'10)

$$\left(\vec{B}\vec{\nabla}\right)\vec{\Omega} = 0 \quad +$$



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- requirement on α':

$$M_{th} = \frac{\omega'_{pl}}{\sqrt{\gamma_c}} = \sqrt{\frac{4\pi\alpha' \cdot 2n_c}{\gamma_c m_c}} \simeq \sqrt{1.5\,\alpha'}\, T_c,\ M_{th} \ll M \Rightarrow \alpha' \ll 0.7 \left(\frac{M}{T_c}\right)^2$$

$$\alpha' \ll 10^{-4} \left(\frac{T_c}{\text{keV}}\right)^{-2}$$

- energy of the ultrarelativistic millicharge gas increases until the heat fluxes are equilibrated, the present-day system is stationary

Solar plasma heating

- millicharges + electrons, Coulomb: $\sigma \sim \alpha^2 \varepsilon^2$
- energy transfer: $\Delta\omega_c = \frac{\omega_c}{m_e} \cdot (\xi T - \omega_c) \cdot (1 - \cos\theta)$
- cross section:

$$d\sigma = \frac{\varepsilon^2 e^4}{8\pi\omega_c^2} \cdot \frac{(1 - x/2)\, dx}{(x + \psi)^2}, \quad x = 1 - \cos\theta, \quad \psi = \omega_{pl}^2/(2\omega_c^2)$$

- heating:

$$Q = 2n_e n_c \left\langle \int \Delta\omega_c \, d\sigma \right\rangle = \frac{\varepsilon^2 e^4 n_e n_c}{4\pi m_e} \cdot \left(\frac{T}{T_c} - 1 \right) \cdot \mathrm{K}\left(\frac{4T_c^2}{\omega_{pl}^2} \right)$$

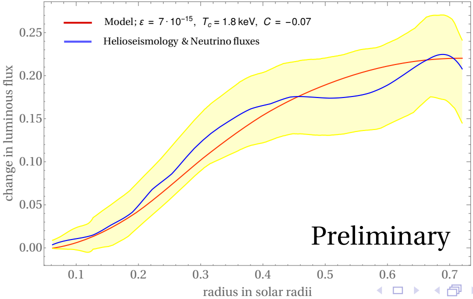
$$\mathrm{K}(a) \equiv \frac{2}{3\zeta(3)} \int_0^\infty dx \, \frac{x^2 \left(\ln ax^2 - 1 \right)}{e^x + 1}$$

Variation of the luminous flux power profile

- Calculate luminous flux change due to the heating:

$$\delta l_c(r) = -\frac{4\pi R_\odot^3}{L_\odot} \cdot \int_0^r Q(x)\, x^2\, dx$$

- Fit parameters of the model to the solar data:



To summarize

- We studied the general energy transfer solutions to the solar abundance problem
- We found the variation of the luminous flux power profile that is required to solve the solar abundance problem
- We showed that solely the emission of particles cannot solve the problem, moreover helioseismology cannot provide bounds on such emission from the tachocline region
- The example of a physical model was suggested which can alleviate the discrepancies

Thank you for your attention!

Exclusion plot for millicharges

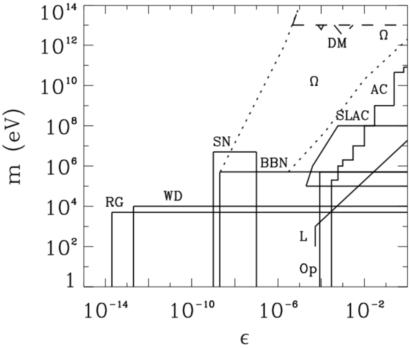


Figure 1: Regions of mass-charge space ruled out for milli-charged particles. The solid and dashed lines apply to the model with a paraphoton; solid and dotted lines apply in the absence of a paraphoton. The bounds arise from the following constraints: AC—accelerator experiments; Op—the Tokyo search for the invisible decay of ortho-positronium [26]; SLAC—the SLAC milli-charged particle search [27]; L—the Lamb shift; BBN—nucleosynthesis; Ω — $\Omega < 1$; RG—plasmon decay in red giants; WD—plasmon decay in white dwarfs; DM—dark matter searches; SN—Supernova 1987A.