Stars and their variability observed from space
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A SOLUTION TO THE "SOLAR ABUNDANCE" PROBLEM

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Abstract. We report a solution to the long-standing "solar abundance" problem. Solar models that include three extra physical processes (convective overshoot, solar wind and PMS accretion) which are missing from standard solar models are shown to be consistent simultaneously with helioseismic inferences (the depth and helium abundance of the convection zone and profiles of sound speed and density), the observed solar Li abundance, and solar neutrino fluxes.

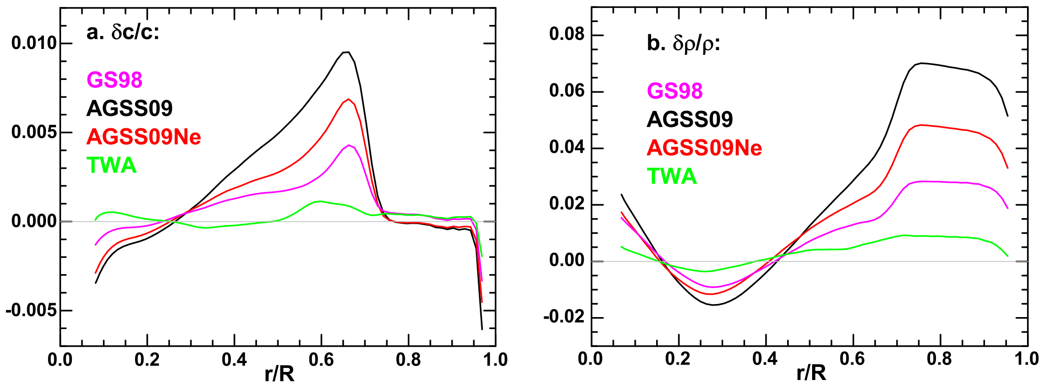
Keywords: Convection, the Sun: abundances, the Sun: interior

1 The "solar abundance" problem

The standard solar model with revised solar composition (AGSS09, Asplund et al. (2009)) cannot be consistent with helioseismic inferences (sound speed and density profiles, $R_{\rm bc}$, and $Y_{\rm S}$). This is called the "solar abundance" problem. The recent measurement of Ne abundance by Young (2018) showed an enhancement of $\sim 40\%$ in the solar photospheric Ne abundance, denoted as AGSS09Ne composition. However, revising the Ne abundance still does not solve the problem.

Since 2004 many extra mechanisms have been tested, but no satisfactory solution has been found. This contribution proposed a different mechanism. If solar models (e.g., Model TWA) can include convective overshooting, PMS helium-poor accretion and a helium-poor solar-wind mass loss, they then show very good agreement simultaneously with helioseismic inferences: sound speed and density profiles, $R_{\rm bc}$, and $Y_{\rm S}$), the solar lithium abundance, and solar neutrino fluxes.

Model TWA is a typical improved solar model that includes the extra physical processes described below. Neither opacity nor micro diffusion enhancement is assumed.



model	GS98	AGSS09	AGSS09Ne	TWA	the Sun
$M_{\rm acc}/M_\odot$	——	——	——	0.0585	——
$M_{\rm L}/M_\odot$	——	——	——	0.0028	0.001−0.03
$Y_{\rm S}$	0.2453	0.2381	0.2405	0.2450	0.2485(35)
$(Z/X)_{\rm S}$	0.0229	0.0181	0.0188	0.0188	0.0188(12)
$R_{\rm bc}/R_\odot$	0.7152	0.7239	0.7207	0.7110	0.713(1)
A(Li)	2.44	2.73	2.60	0.82	1.05(10)
neutrino fluxes in ($\rm cm^{-2}s^{-1}$)					
^{7}Be (10^9)	4.91	4.63	4.70	4.84	4.80(5%)
^{8}B (10^6)	5.35	4.74	4.89	5.13	5.16(2.2%)

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2 Extra physical processes in Model TWA

2.1 Convective overshoot below the convection envelope

Convective overshoot has two effects: the kinetic energy flux below the base of the convection zone (CZ), and overshoot mixing. A simple model to describe the kinetic energy flux of the overshoot below the CZ base is

$$L_{\rm K}(r) = -\beta L(r)[\frac{P(r)}{P_{BCZ}}]^{(-1/\theta)}, \text{for } r \leq r_{BCZ}, \tag{2.1}$$

where P_{BCZ} is the pressure at the base of the CZ r_{BCZ}, $\beta = 0.13$ and $\theta = 0.2$ (based on helioseismic inferences). The kinetic energy flux in the CZ has little effect on solar models, sp there is an arbitrariness to set $L_{\rm K}$ in the CZ. To retain a smooth profile for $L_{\rm K}$, it is set as

$$L_{\rm K} = -\beta L(r) \exp\left(\frac{x}{\sqrt{x^2+1}}\right) f(\log T(r), 5.7, 6.2), \text{for } r > r_{BCZ}, \tag{2.2}$$

where $x(r) = \ln[P(r)/P_{BCZ}]$ and

$$f(y,a,b) = \begin{cases} 1, y > b \\ \frac{1}{2} + \frac{1}{2}\sin[(\frac{y-a}{b-a} - \frac{1}{2})\pi], a \leq y \leq b \\ 0, y < a \end{cases} . \tag{2.3}$$

The diffusion coefficient for the overshoot mixing is modelled as (Zhang 2013):

$$D_{\rm OV} = C_{\rm X}\frac{\varepsilon_{\rm turb}}{N^2} = -\frac{C_{\rm X} g L_{\rm K}}{4.4\pi\theta r^2 P N^2}, \tag{2.4}$$

where $\varepsilon_{\rm turb}$ is the rate of dissipation of turbulent kinetic energy, and $C_{\rm X} = 5 \times 10^{-4}$ (based on the solar lithium abundance).

2.2 Solar wind

Observations have shown that the helium abundance in the solar wind is about half its abundance in the CZ, owing to the effect of the first ionization potential (FIP). The solar-wind mass-loss rate was estimated as ${\rm d}M/{\rm d}t \propto t^{-2.00\pm0.52}$ and reaches saturation before 0.1 Gyr (Wood et al. 2002).

The adopted solar-wind mass-loss rate is

$$\frac{{\rm d}M}{{\rm d}t} = -Ct^{\gamma}, \text{for } t > 0.1\text{Gyr}, \tag{2.5}$$

where adjustments in C and γ have been based on the total mass loss of $0.0028M_{\odot}$ and the present solar-wind mass-loss rate, ${\rm d}M/{\rm d}t = -2 \times 10^{-14} M_{\odot}{\rm yr}^{-1}$. The composition of the solar wind, based on its helium-poor property, is then set as

$$(X_{\rm L}, Y_{\rm L}, Z_{\rm L}) = \frac{(X_{\rm S}, 0.5Y_{\rm S}, Z_{\rm S})}{X_{\rm S} + 0.5Y_{\rm S} + Z_{\rm S}}, \tag{2.6}$$

2.3 PMS accretion

PMS accretion is a common property in solar-mass stars. The mass accretion rate, adopted from (Hartmann et al. 2016), is

$$\log[\frac{d(M/M_{\odot})}{d(t/{\rm yr})}] = -1.32 - 1.07\log(t/{\rm yr}) + 2.1\log(\frac{M/M_{\odot}}{0.7}). \tag{2.7}$$

The accretion starts at age 2Myr and ends at 12Myr, with a total accreted mass of $0.0585M_{\odot}$. The composition of the accreted materials is assumed to be $Z_{\rm acc} = 0.015$ and $Y_{\rm acc} = 0.07$. We also assumed that accretion in the PMS magnetosphere is ion-dominated, so the FIP effect could lead to inhomogeneous accretion. The composition of the accreted materials could therefore be different from the primordial composition.

3 Link to publication

A paper on this topic has been published by Zhang, Li, & Christensen-Dalsgaard, in ApJ 881, 103, 2019.

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