PHY 474/374 — Spring 2021

Week 7—Monday, May 10—Discussion Worksheet

The Sun

The Sun allows not only for a test of stellar models, but also the opportunity to verify them with exquisite precision not afforded by any other star. You will look at a model of the present Sun in more detail on the homework. For now, let's look at how the Sun has evolved over time.

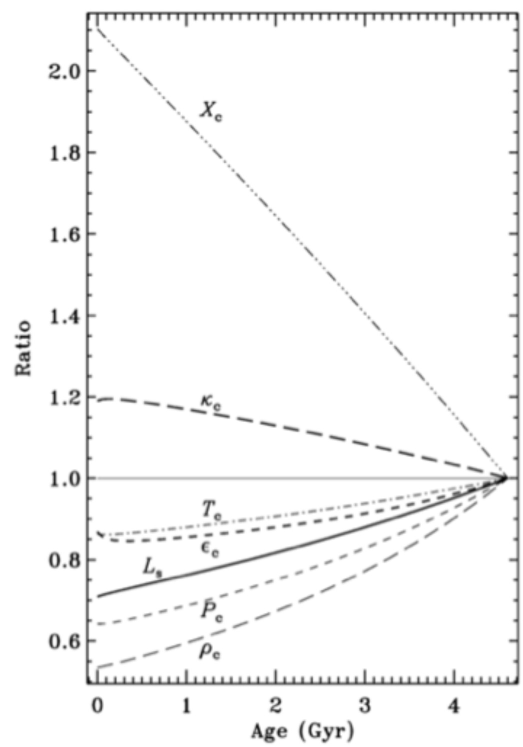
1. Consider the graph below, taken from Figure 11.8 in *Dalsgaard*. All variables have been normalized with respect to their value in the present-day Sun.

(a) Comment on whether the core of the Sun is hotter now than it was at ZAMS by finding the percentage by which its core temperature has changed.

Core temperature

$$\frac{0.05 \text{ (Retro)}}{1 \text{ Gyr}}$$

$$\left(\frac{1-0.85}{1}\right) \times 100 = 15\%$$



(b) Over time, the mass fraction X of hydrogen decreases in the core. If the value at ZAMS was $X = 0.709$, use the graph to figure out the hydrogen mass fraction in the present-day Sun.

$$\frac{0.709}{2.15} = 0.338$$

2. We will now consider the implications of the changes we calculated on the previous page.

(a) Discuss how the change in X will impact μ, hence ρ_c, and in turn, T_c. Recall that

$$\mu = \frac{4}{3+5X-Z} \qquad n = \frac{\rho}{\mu m_p} \qquad T_c = \frac{G\mu_c m_p M}{k_B R}$$

Do your conclusions agree with the plots on the previous page?

$\downarrow$ in X will $\uparrow$ μ

$\uparrow$ in ρ since $\rho = \underbrace{n m_p}_{\text{const}} \underbrace{\mu}_{\uparrow}$

$\uparrow$ in T_c since μ $\uparrow$

(b) Changes in T_c should impact ϵ_c, the rate of energy generation at the center, since $\epsilon_c \propto \rho X^2 T^4$. Use the plot on the previous page to find by how much ϵ_c has changed from ZAMS to the present-day Sun. Why is this such a modest change, considering the change in T_c?

Because of the massive temp drop off in X

$(\epsilon_c)_{ZAMS} = 0.85\,(\epsilon_c)$

Change in ϵ_c is about ~15%

$\epsilon_c \propto T^4$

3. The change in ϵ_c you found on the previous page may be modest, but it has resulted in a significant change to the surface luminosity of the Sun from ZAMS until today.

(a) Use the plot in Question 1 to find the percentage change in the luminosity of the Sun from ZAMS to the present day.

$$L$$

$$(L_s)_{ZAMS} = 0.7\,(L_s)_{today}$$

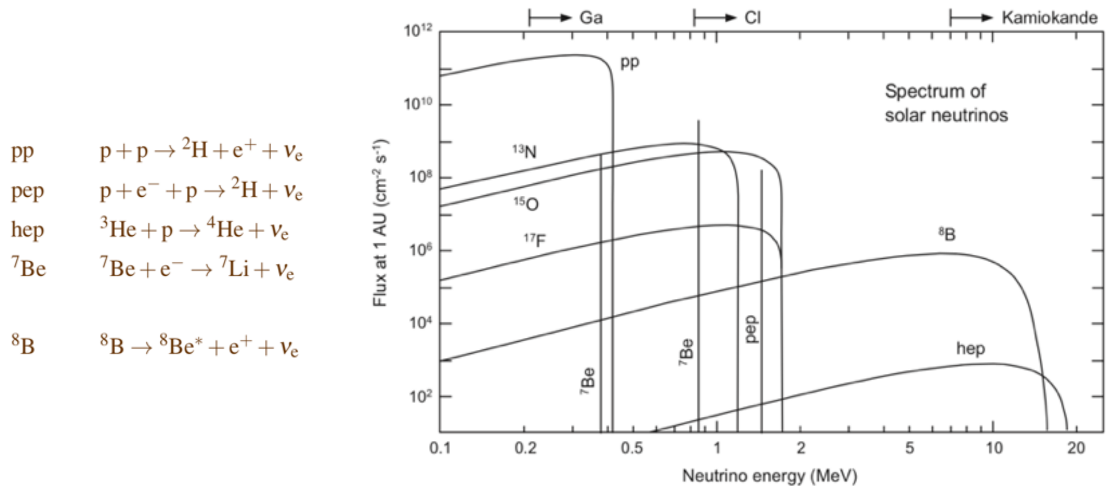
$$\left(\frac{1-0.7}{1}\right) \times 100 = 30\%$$

(b) Despite the modest change in ϵ_c, discuss what factor is most responsible for communicating this change to the surface, enabling L to change by the amount you calculated. Use the plots on the previous page.

Along with ↑ of ϵ_c, opacity (κ_c) in the interior falls, so radiation results from the ↑ ϵ_c can be communicated effectively to the surface, ↑ the surface luminosity

Solar neutrinos carry significant and immediate information about conditions in the solar core.

4. Consider the energy spectrum of neutrinos predicted by a model of the present-day Sun shown below, where the y-axis gives the flux of neutrinos at 1 AU. The reactions shown in the figure are written out in full in the left panel; note that we did not discuss pep and hep last week. Ignore the reactions marked ^{13}N, ^{15}O, and ^{17}F; they belong to the CNO cycle which makes only modest contributions to the solar neutrino flux.



(a) The pioneering experiment to detect solar neutrinos was started by Raymond Davis in the early 1960s. It uses the reaction

$$\nu \; + \; ^{37}\text{Cl} \;\; \rightarrow \;\; ^{37}\text{Ar} \; + \; e^-$$

in a detector comprised of 600 tons of cleaning fluid (C_2Cl_4), placed 1500 m below ground in the abandoned Homestake gold mine in South Dakota. As marked in the figure above, the threshold minimum for this reaction to occur is 0.8 MeV. To which of the 5 reactions marked above is this detection method sensitive (in principle)?

^8B $\quad$ $^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

(b) Another detector uses gallium to detect solar neutrinos via the reaction

$$\nu \; + \; ^{71}\text{Ga} \;\; \rightarrow \;\; ^{71}\text{Ge} \; + \; e^-$$

and has a threshold of only 0.23 MeV (see figure above). The ability to detect which of the above 5 reactions gives this method a unique advantage? Why is the detection of this reaction important?

pp $\quad$ $p + p \rightarrow {}^2H + e^+ + \nu_e$

90% of Sun's energy is produced by PP-1 chain

5. The table below shows solar neutrino fluxes from various experiments compared with a Standard Solar Model (SSM). All fluxes are in Solar Neutrino Units (SNU), where SNU is defined as 10^{-36} captures per target atom in the detector per second. Note that I've suppressed the systematic and statistical errors for brevity. The second and third entries (SAGE and GALLEX) refer to the Ga-based detection.

Experiment	Observed flux (SNU)	SSM (SNU)	Observed/SSM
Homestake	2.54	9.3	0.27
SAGE	72	137	0.53
GALLEX	69.7	137	0,51

(a) Fill in the last column in the table with the ratio of observed neutrino flux to that predicted by a Standard Solar Model (SSM).

(b) Discuss what your calculations tell you about the observed vs. predicted neutrino flux.

Flux is less than predicted nutrino flux

(c) There are two possible reasons for the discrepancy identified in your answer in part (b). What are they?

- Standard solar model is wrong
- knowledge of neutrinos is wrong