

Physics 681: Solar Physics and Instrumentation – Lecture 5

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Equation of State

- Express ρ as a function of (P, T)
- Minimize free energy:

$$P = -\left(\frac{\partial F}{\partial V}\right)_{T,n} \quad \text{and} \quad P = -\left(\frac{\partial F}{\partial T}\right)_{V,n}$$

- Pressure \Leftrightarrow momentum of particles and photons (gas and radiation pressure)

$$P = P_G + P_R \quad P_G = \beta P \quad P_R = (1 - \beta) P_R \quad \text{with} \quad P_R = \frac{4\sigma}{3c} T^4$$

- Perfect gas pressure:

$$P_{PG} = \frac{\rho \mathcal{R} T}{\mu} \quad \text{with} \quad \mu_0 = 1 / (X + Y/4 + Z/2) \quad \text{and} \quad \mu = \mu_0 / (1 + E)$$

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Standard Solar Model

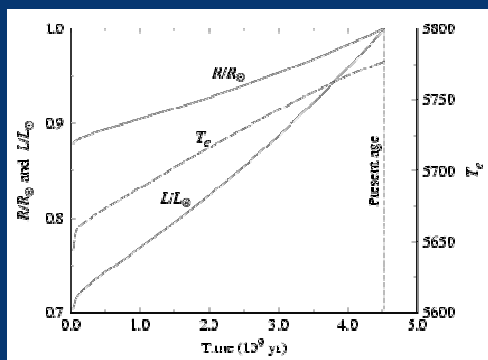
- ❑ Approach from Hayashi line to ZAMS in about 5×10^7 yr (Helmholtz-Kelvin time-scale)
- ❑ 4.57×10^9 yr on main-sequence
- ❑ Little change of luminosity and effective temperature
- ❑ How would a change of luminosity affect Earth (dramatic cooling, life on Earth)?
- ❑ Convection zone contains only 2.5% of the total mass
- ❑ Only 10% of the mass is contained beyond $r/r_{\odot}=0.5$ (7/8 of the volume!)



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Solar Evolution



Carol & Ostlie (1996)

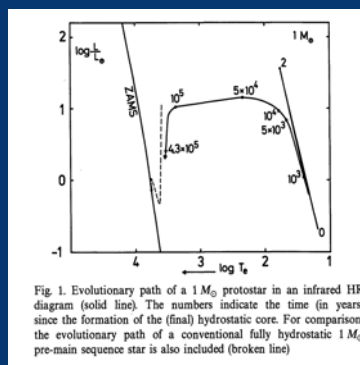


Fig. 1. Evolutionary path of a $1 M_{\odot}$ protostar in an infrared HR diagram (solid line). The numbers indicate the time (in years) since the formation of the (final) hydrostatic core. For comparison, the evolutionary path of a conventional fully hydrostatic $1 M_{\odot}$ pre-main sequence star is also included (broken line)

Appenzeller & Tschamuter (1975)



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Mid-Term Exam – Instrumentation

- Angelo ⇒ “Fabry-Pérot Interferometer”
- Changyi ⇒ “LAMOST”
- Garrett ⇒ “ATST”
- Joseph ⇒ “Neutrino Detectors”
- Hui ⇒ “MDI”
- Preethi ⇒ “RHESSI”
- Sam ⇒ “LASCO”
- ApJ style files:

<http://www.journals.uchicago.edu/ApJ/information.html>

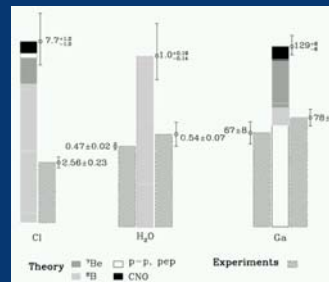
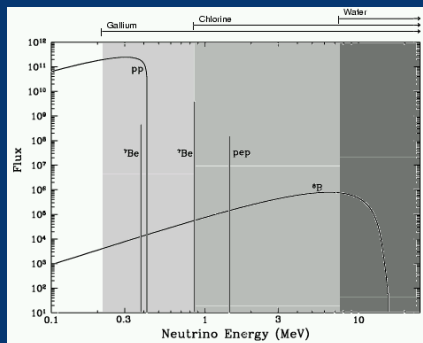


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Neutrinos

- “pep” reaction (0.25): $p(p e^-, \nu)d$ with $Q_\nu = 1.442$ MeV
- “pp” chain important for total energy



<http://www.astro.utu.fi/~cflynn/Stars/18.html>

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- ❑ Continuous spectra (β -decay, angular momentum and energy conservation)
- ❑ Line spectra (pep, ${}^7\text{Be}$ electron capture (0.862 MeV and 0.384 MeV))
- ❑ Spectral distribution is strongly temperature dependent
- ❑ ${}^{37}\text{Cl}$ threshold 814 keV (8.76 snu)
- ❑ ${}^{71}\text{Ga}$ threshold 233 keV (129.2 snu)
- ❑ 1 snu = 1 capture per second per 10^{38} target atoms
- ❑ Experiments confirm:
 - Nuclear energy generation in the Sun
 - Neutrino flux is significantly below values expected from Standard Solar Model
 - This discrepancy depends on the energy of the neutrinos
- ❑ Non-Standard Solar Models?
- ❑ Neutrino oscillations (Mikheyev-Smirnow-Wolfenstein (MSW effect)) in the presence of other matter (deep interior of the Sun)



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Non-Standard Solar Models

- ❑ Low- Z model "dirty solar model"
 - Heavy metals contribute disproportionately to opacity \Rightarrow smaller temperature gradient \Rightarrow smaller central temperature
 - Energy production reduced but luminosity constant
 - $Z = 0.001$ explains ${}^{37}\text{Cl}$ results (outer layers \Rightarrow accretion from passage through clouds of interstellar medium)
 - Problem: initial Helium abundance ($Y_0 = 0.20$), "Big Bang" ($Y_0 = 0.23$)
- ❑ Rapidly rotating core
 - Use rotation to adjust pressure P ($500 \times$ surface rotation rate)
 - Problem: Oblateness (deformation of outer layers)
- ❑ Internal magnetic field
- ❑ Internally mixed model
- ❑ Helioseismology (splitting of oscillation frequencies)!



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