Nuclear Fusion in Substellar Objects

PHY 688, Lecture 16
Mar 4, 2009
Outline

• Review of previous lecture
  – substellar evolution
  – analytical solution for $L(t)$ and $T_{\text{eff}}(t)$

• The hydrogen burning limit

• Lithium and deuterium burning
Previously in PHY 688...
Hydrogen phase diagram

Evolution is towards:
- lower entropy $S$
- higher degeneracy $\eta$

(Burrows & Liebert 1993)
Evolution of $L$ and $T_{\text{eff}}$

\[
\frac{d\eta}{dt} = 2.04 \times 10^{-14} \left( \frac{0.05 M_\odot}{M} \right)^{1.028} \left( \frac{10^{-2}}{\kappa_R} \right)^{1.184} \frac{(1 + \alpha/\eta)^{0.64}}{\eta^{2.352}}.
\]

If we ignore the early evolution and assume that $\eta \gg 1$, we can drop the result is

\[
\eta = 9.8 \left( \frac{t}{10^9 \ \text{yr}} \right)^{0.298} \left( \frac{0.05 M_\odot}{M} \right)^{0.307} \left( \frac{10^{-2}}{\kappa_R} \right)^{0.353},
\]

which, after substituting into Eqs. (2.53) and (2.55), gives us

\[
T_e = 1551 K \left( \frac{10^9 \ \text{yr}}{t} \right)^{0.324} \left( \frac{M}{0.05 M_\odot} \right)^{0.827} \left( \frac{\kappa_R}{10^{-2}} \right)^{0.088}
\]

and

\[
L = 3.82 \times 10^{-5} L_\odot \left( \frac{10^9 \ \text{yr}}{t} \right)^{1.297} \left( \frac{M}{0.05 M_\odot} \right)^{2.641} \left( \frac{\kappa_R}{10^{-2}} \right)^{0.35}.
\]

(Burrows & Liebert 1993)
Evolution of Effective Temperature

(Burrows et al. 2001)
Evolution of Luminosity

(Burrows et al. 2001)
Evolution of Nuclear (Fusion) vs. Total Luminosity

\[ L_n/L \text{ vs Time} \]

\[ \log_{10}[\text{Time (Years)}] \]

\[ 0.080 \, M_{\text{Sun}} \]
\[ 0.075 \, M_{\text{Sun}} \]
\[ 0.070 \, M_{\text{Sun}} \]
\[ 0.060 \, M_{\text{Sun}} \]

(Burrows & Liebert 1993)
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The Minimum Main-Sequence Mass

- Derive by equating nuclear energy generation to energy loss through cooling.

\[
\frac{dE}{dt} + P \frac{dV}{dt} = T \frac{dS}{dt} = \dot{\varepsilon} - \frac{\partial L}{\partial M} = 0
\]

- Have expression for \( L(M, \kappa_R, \eta) \)
- Find expression for \( \dot{\varepsilon}(M, \eta) \)
From Lecture 14: Energy Generation is Enhanced in Electron Degenerate Dwarfs

• unscreened energy generation rates for $^1$H + $^1$H ($p + p$) and $^1$H + $^2$H ($p + d$):

\[
\dot{\varepsilon}_{pp} = 2.5 \times 10^6 \left( \rho X^2 / T_6^{2/3} \right) e^{-33.8/T_6^{1/3}} \text{ ergs gm}^{-1}\text{cm}^{-1}
\]

\[
\dot{\varepsilon}_{pd} = 1.4 \times 10^{24} \left( \rho XY_d / T_6^{2/3} \right) e^{-37.2/T_6^{1/3}} \text{ ergs gm}^{-1}\text{cm}^{-1}
\]

$Y_d$ is $^2$H mass fraction (primordial value is $2 \times 10^{-5}$)

• but recall that H is in a state of strongly coupled plasma \((\Gamma = Z^2 e^2/r_s kT > 1)\)
  
  – proton and deuteron screening decreases Coulomb barrier
  
  – $p + p$ and $p + d$ rates enhanced by factor of

\[
S \approx e^{H(0)}, \quad \text{where} \quad H(0) \approx \min(0.977\Gamma^{1.29}, 1.06\Gamma)
\]

  – at main sequence edge $S \sim 2$; can be higher at lower masses

\[
\dot{\varepsilon}_{pp} \propto T^{6.31} \rho^{1.28} \text{ in core of transition mass object}
\]

\[
\dot{\varepsilon}_{pp} \propto T^4 \rho \text{ in core of the Sun}
\]
p-p Chain Reaction Rate is Decided by the First Step (p+p)
The Minimum Main Sequence Mass

- Depends slightly on metallicity
  - He content
  - atmospheric opacity
- At $[m/H] = 0.0$ (solar metallicity):
  - $M_{\text{MMSM}} \approx 0.075 \, M_{\text{Sun}}$
  - $L_{\text{MMSM}} \approx 6 \times 10^{-5} \, L_{\text{Sun}}$
  - $T_{\text{eff, MMSM}} \sim 1600–1750 \, K$
- At $[m/H] \rightarrow -\infty$ (zero metallicity)
  - $M_{\text{MMSM}} \approx 0.092 \, M_{\text{Sun}}$
  - $L_{\text{MMSM}} \approx 1.3 \times 10^{-3} \, L_{\text{Sun}}$
  - $T_{\text{eff, MMSM}} \sim 3600 \, K$
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Lithium and Deuterium Burning: the Fastest Fusion Reactions
Lithium and Deuterium Burning

stars
brown dwarfs
“planets”

Li and H burning: at $> 2.7 \times 10^6$ K

D burning: at $> 4 \times 10^5$ K

(Burrows et al. 2001)
Deuterium Depletion

(Burrows et al. 2001)
Lithium Depletion

(Burrows et al. 2001)
Li and D: Depleted within Few 100Myr

(Burrows et al. 2001)
Lithium is Observable in the Photosphere

(Kirkpatrick et al. 1999)
The Lithium Test for Age/Substellarity

(Burrows et al. 2001)
The Lithium Test for Age/Substellarity presence of Li:

- youth

and/or

- substellar mass
1995: Teide 1 – First Bona-Fide Brown Dwarf

- member of 100 Myr-old Pleiades open cluster
  - Rebolo et al. (1995)
- spectroscopic signature of lithium in absorption
  - Rebolo et al. (1996)
  - destroyed in the convective interiors of low-mass stars
- ...but initially
  - insufficient sensitivity to detect Li (at 6708 Å)
  - skepticism about age

(Rebolo et al. 1995)
Teide spectrum (Rebolo et al. 1996)
The Lithium Test for Age/Substellarity

presence of Li:

• youth

and / or

• substellar mass

(Basri 1997)