Substellar Evolution

PHY 688, Lecture 15
Outline

• Review of previous lecture
  – fusion in brown dwarf interiors
  – towards an analytical solution to the EOS

• Substellar Evolution
  – analytical solution for $L(t)$ and $T_{\text{eff}}(t)$
Previously in PHY 688...
Cooling and Nuclear Burning

- substellar contraction stops
  - by ignition of thermonuclear fuel
  - by onset of degeneracy
- thermonuclear rates depend on both $T$ and $\rho$
  - $T_{\text{ignition}}$ is a function of $\rho$
  - in lowest mass star, $T_c$ decreases at final stages before stabilizing because of increase in $P$
- thermonuclear burning in brown dwarfs
  - H for billions of years at $>0.070\, M_{\odot}$ (unsustained)
  - D ($^2\text{H}$), Li for 10–100 Myr (i.e., also unsustained)

(Burrows et al. 2001)
Energy Generation in Low-Mass Stars and Brown Dwarfs

• *From Lecture 4:*

![Diagram of proton-proton (pp) chain in Sun]

$Q = 1.44 \text{ MeV} \quad Q = 5.49 \text{ MeV}$

reaction stops here for $<0.25 \, M_{\text{Sun}}$ stars
Energy Generation is *Enhanced* in Low-Mass Stars and Brown Dwarfs

- unscreened energy generation rates for $^1\text{H} + ^1\text{H} (p + p)$ and $^1\text{H} + ^2\text{H} (p + d)$:
  \[
  \dot{\varepsilon}_{pp} = 2.5 \times 10^6 \left( \rho X^2 / T_6^{2/3} \right) e^{-33.8/T_6^{1/3}} \text{ ergs gm}^{-1}\text{cm}^{-1}
  \]
  \[
  \dot{\varepsilon}_{pd} = 1.4 \times 10^{24} \left( \rho X Y_d / T_6^{2/3} \right) e^{-37.2/T_6^{1/3}} \text{ ergs gm}^{-1}\text{cm}^{-1}
  \]
  $Y_d$ is $^2\text{H}$ 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
    \[
    S \approx e^{H(0)}, \quad \text{where } H(0) \approx \min(0.977 \Gamma^{1.29}, 1.06 \Gamma)
    \]
    - at main sequence edge \( S \sim 2 \); can be higher at lower masses
      \[
      \dot{\varepsilon}_{pp} \propto T^{6.31} \rho^{1.28} \text{ in core of transition mass object}
      \]
      \[
      \dot{\varepsilon}_{pp} \propto T^4 \rho \text{ in core of the Sun}
      \]
Analytic Model of Brown Dwarfs

• Brown dwarfs
  – are fully convective, hence isentropic
  – have an EOS that is polytropic both above and below the plasma phase transition
  – can be solved analytically

• Goal: solve for evolution of substellar $L$ and $T_{\text{eff}}$, mass burning limits
  – and learn something along the way!
Hydrogen phase diagram

Adiabats are tracks of $\eta \sim \text{const}$

(Burrows & Liebert 1993)
Cooling and Nuclear Burning

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From Lecture 1: BDs—a Theoretical Expectation

- Kumar (1963)
  - modeling of $<0.1M_{\text{Sun}}$ stars
  - importance of electron degeneracy

- minimum mass below which objects can not fuse H
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Hydrogen phase diagram

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

(Burrows & Liebert 1993)
0.05 $M_\odot$
Brown dwarf at 5 Gyr

($X = 100\% \text{ H}$)

(1 bar = $10^6 \text{ dyn/cm}^2 = 0.99 \text{ atm}$)

$P \approx 5 \text{ bar, } T \approx 1000 \text{ K, } \rho \approx 10^{-4} \text{ g/cc}$

$P \approx 10^{11} \text{ bar, } T \approx 10^6 \text{ K, } \rho \approx 500 \text{ g/cc}$

(Phase change?)
Evolution of Effective Temperature

(Burrows et al. 2001)
Evolution of Luminosity

(Burrows et al. 2001)