

# Stellar Astronomy and Astrophysics (SS09):

## Exercise 3 (for May 18, 2009)

### 1. Polytropic spheres:

The Lane-Emden equation for a polytropic index  $n$  ( $P = K\rho^\gamma = K\rho^{(n+1)/n}$ ) is

$$\frac{1}{\xi^2} \frac{d}{d\xi} \left[ \xi^2 \frac{dD_n}{d\xi} \right] = -D_n^n,$$

where  $\rho(r) = \rho_c [D_n(r)]^n$  with  $0 \leq D_n \leq 1$ , and where  $r = \lambda_n \xi$  with  $\lambda_n = \left[ (n+1) \left( \frac{K\rho_c^{(1-n)/n}}{4\pi G} \right) \right]^{1/2}$ . The surface is defined by  $D_n(\xi_{\text{surf}}) = 0$ , and the inner boundary is  $dD_n/d\xi = 0$  at  $\xi = 0$ .

(a) Show that the  $n = 0$  polytrope has a solution given by

$$D_0(\xi) = 1 - \frac{\xi^2}{6}, \quad \text{with } \xi_{\text{surf}} = \sqrt{6}.$$

(b) Show that the  $n = 1$  polytrope has a solution given by

$$D_1(\xi) = \frac{\sin \xi}{\xi}, \quad \text{with } \xi_{\text{surf}} = \pi.$$

(c) Show that the  $n = 5$  polytrope has a solution given by

$$D_5(\xi) = (1 + \xi^2/3)^{-1/2}, \quad \text{with } \xi_{\text{surf}} \rightarrow \infty.$$

Is the total mass finite?

(d) Plot the density structure for  $n = 0, 1$ , and  $5$  ( $\rho_n/\rho_c$  vs.  $r/\lambda_n$ ).

### 2. Hertzsprung-Russell Diagram for Simple Model Stars

Consider a family of chemically homogeneous stars that are similar in every respect except for their masses  $M$  and radii  $R$ . Using a dimensionless radius variable,  $x = r/R$ , we can define similarity functions  $F(x)$  such that

$$\rho(r) = \frac{M}{R^3} F_\rho(x) \quad \text{and} \quad m(r) = M F_m(x).$$

Assume an ideal equation of state for the stellar material, i.e.  $P = \rho k_B T / \mu_m$  with Boltzmann's constant  $k_B$  and mean molecular mass  $\mu_m = \mu m_p$  (where  $\mu$  = mean molecular weight and  $m_p$  = proton mass) and with  $P$  and  $T$  being pressure and temperature. Assume furthermore that energy is transported radiatively with an opacity obeying Kramer's law ( $\kappa \propto \rho T^{-7/2}$ ) and that nuclear energy is generated by the PP chain where the energy production scales as  $\varepsilon_{\text{PP}} \propto \rho^2 T^4$ .

- a) Use the fundamental equations of stellar structure as outlined in the lecture to derive the following scaling relations for pressure  $P$ , temperature  $T$ , and energy flux due to radiative transport  $L_{\text{rad}}$  as well as due to nuclear fusion  $L_{\text{nuc}}$ :

$$\begin{aligned}P(r) &= \frac{M^2}{R^4} F_P(x), \\T(r) &= \frac{M}{R} F_T(x), \\L_{\text{rad}}(r) &= \frac{M^{5.5}}{R^{0.5}} F_{\text{rad}}(x), \\L_{\text{nuc}}(r) &= \frac{M^6}{R^7} F_{\text{nuc}}(x),\end{aligned}$$

where again the  $F$ -functions are common to all family members.

- b) Note that the energy flux transported by radiative diffusion increases slowly while the flux generated by nuclear fusion rises rapidly as the star contracts. Sketch  $L_{\text{rad}}$  and  $L_{\text{nuc}}$  as function of radius. Find the radius and luminosity as function of total mass at which the PP chain can produce enough energy to compensate the radiative losses at the surface. This is when the star reaches a quasi-equilibrium state: the stellar main sequence.
- c) Demonstrate that all stars of the homologous family in this phase lie on a line in the Hertzsprung-Russell diagram with

$$L \propto T_{\text{E}}^{4.12}$$

with  $T_{\text{E}}$  being the effective temperature at the surface.