APPROXIMATE NUCLEAR REACTION RATES FOR PP, CNO, and TRIPLE-ALPHA

A very good and elementary description of some nuclear reaction rates is provided by M. Schwarzschild *(Structure and Evolution of the Stars)* . A more detailed description is in R. Kippenhahn and A. Weigert (*Stellar Structure and Evolution*, pp. 146-173), D. D. Clayton *(Principles of Stellar Structure and Nucleosynthesis)* and H. Reeves (1965, in *Stellar Structure*, Editors: L. H. Aller and D. B. McLaughlin, page 113, The University oc Chicago Press) . The most extensive list of the burning rates for hundreds of nuclear reactions is in M. J. Harris, W. A. Fowler, G. R. Caughlan, and B. A. Zimmerman (1983, *Annual Rev. Astron. Astrophys.,* **21** , 165) .

We shall give here just three rates: two for hydrogen burning (proton - proton and CNO cycles) and one for helium burning (triple alpha) :

$$\epsilon_{pp} \approx 10^6 X_1^2 \rho T_6^{-2/3} e^{-33.81 T_6^{-1/3}}, \qquad [\text{erg s}^{-1}\,\text{g}^{-1}],$$

$$\epsilon_{CNO} \approx 10^{28} \rho X_1 X_{14} \rho T_6^{-2/3} e^{-152.313 T_6^{-1/3}}, \qquad [\text{erg s}^{-1}\,\text{g}^{-1}],$$

$$\epsilon_{3\alpha} \approx 3 \times 10^{11} X_4^3 \rho^2 T_8^{-3} e^{-43.5 T_8^{-1}}, \qquad [\text{erg s}^{-1}\,\text{g}^{-1}],$$

where X_1, X_4, and X_{14} are the abundance, by the mass fraction, of hydrogen, helium, and nitrogen, respectively, and $T_6 \equiv T/10^6\,\text{K}$, $T_8 \equiv T/10^8\,\text{K}$.

The amount of energy released in the three reactions is equal to $E_{pp}^* \approx 6.3 \times 10^{18}\,\text{erg g}^{-1}$, $E_{CNO}^* \approx 6.0 \times 10^{18}\,\text{erg g}^{-1}$, $E_{3\alpha}^* \approx 6.0 \times 10^{17}\,\text{erg g}^{-1}$. A slight difference between E_{pp}^* and E_{CNO}^* is due to a different amount of energy lost by neutrino emission. The changes in chemical composition can be calculated according to

$$\frac{dX_1}{dt} = -\frac{\epsilon_{pp}}{E_{pp}^*} - \frac{\epsilon_{CNO}}{E_{CNO}^*},$$

$$\frac{dX_4}{dt} = \frac{\epsilon_{pp}}{E_{pp}^*} + \frac{\epsilon_{CNO}}{E_{CNO}^*} - \frac{\epsilon_{3\alpha}}{E_{3\alpha}^*},$$