Handout 17: Stellar Luminosities

- The complicated atomic physics
  - Cross sections vs. wavelength for each mechanism
    - Free-free, bound-bound, free-bound, e-scattering
  - And each atom and ion
    - H, H+, H-, e-
    - He, He+, He++
    - O, O+, O++, O+++, etc.
    - Fe, Fe+, Fe++, Fe+25
  - Assuming T.E. of ionization and excitation

Opacities, luminosities

- Are summarized in Fig. 9.10
  - Recall we seek the layer with the highest resistance to radiative energy transport
  - Recall interior temperatures are 1 to 10 million K
  - We will see later, that when the resistance (κ) gets very high
    - The temperature gradient $|dT/dr|$ gets large
    - Leading to convection
      - Which is very efficient at transporting energy

Opacities

- For moderate interior T's, the opacity is dominated by free-bound from ions
  - i.e. above 40,000 K, H and He totally ionized
  - But O still has OIV, OV, OVI, and OVII ions
  - There will always be some ions
    - Until Fe is completely ionized above 10^7 K
  - At these T's, the opacity, first calculated by Kramers, is (for solar abundances):

$$\kappa(\rho, T) = 10 \cdot \left(\frac{\rho}{gm \cdot cm^{-3}}\right)^{1} \cdot \left(\frac{T}{10^{6.5} \cdot K}\right)^{-3.5} \cdot \frac{cm^2}{gm}$$

Kramers' f-f and f-bounc

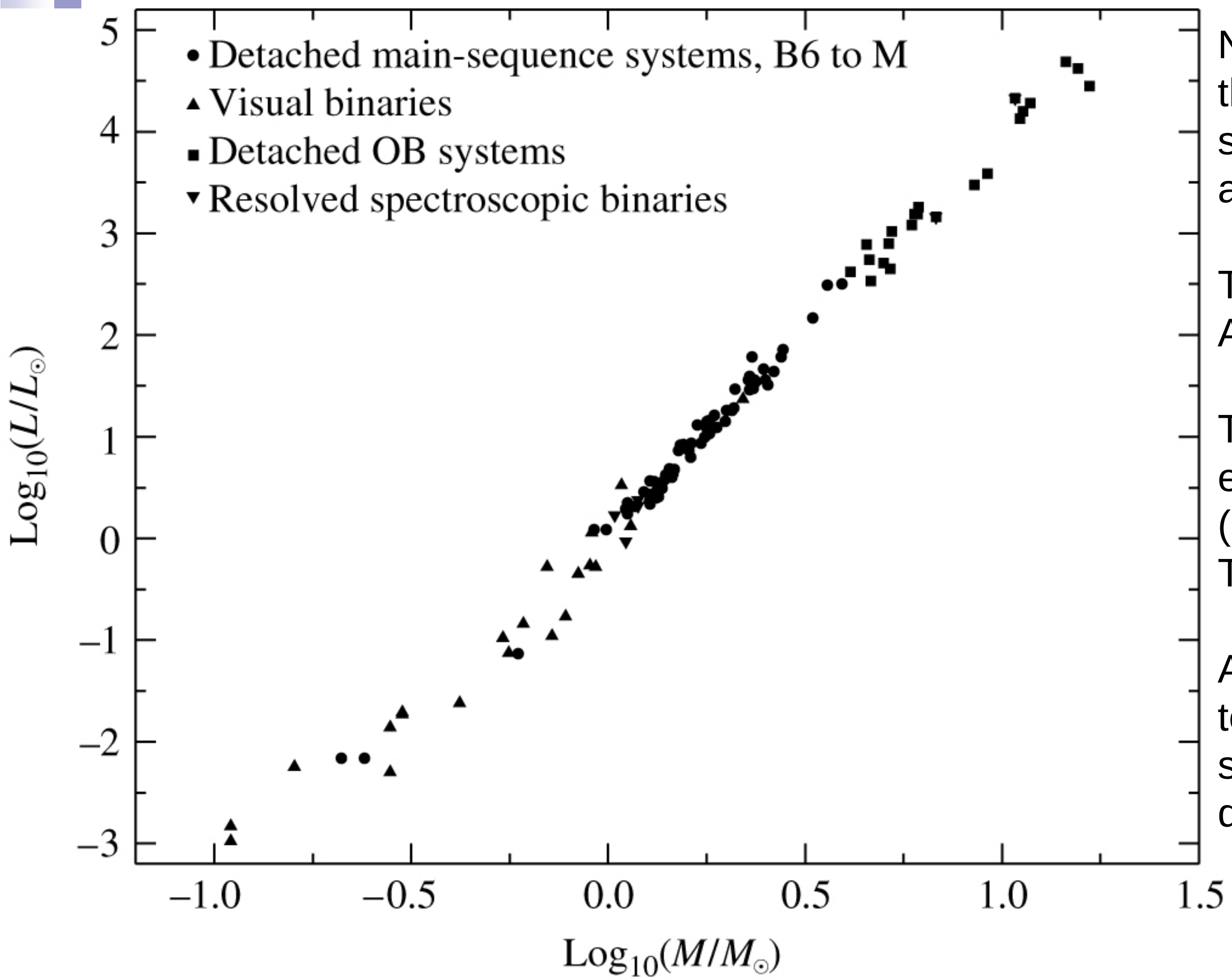
Minimum opacity, e-scattering

- At the highest T's, all atoms are totally ionized
  - The free-free opacity is very small
  - The total opacity is dominated by e-scattering
- Calculate κ
  - Consider 10 H atoms + 1 He atom
  - $M = 14\ m_{Hydrogen}$, $\sigma = 12\ \sigma_{Thompson}$
  - $\kappa = \sigma/M = 0.3\ cm^2/gm$
    - Independent of ρ and T
    - See Fig. 9.10

Dependence of Luminosity on Mass and Radius

- Substituting typical (i.e. average) quantities for the T, dT/dr, ρ, and r
  - $L \sim (1/\kappa\rho) r^2 T^3 |dT/dr| \sim M^3/\kappa$
  - If κ is independent of ρ and T, $L \sim M^3$
    - This is just what is seen on the upper end of the main sequence (c.f. Fig. 7.7)
    - These stars are hot, the opacity is dominated by e-scattering.
    - The evolutionary tracks on the H-R diagram are horizontal
      - i.e. Luminosity independent of Radius!

Fig. 7.7 from Carroll & Ostlie (the Mass-Luminosity relationship for Main Sequence stars)



Notice that at high masses, the data points follow a straight line with a slope about 3 on this Log-Log plot.

This implies $L = AM^3$, where A is a constant.

This is exactly the law expected if opacity κ (cm^2/gm) is independent of T and density!

At the high interior temperatures of high-mass stars, the opacity is dominated by e-scattering!

Evolution on H-R diagram of hot stars

- Star contracts until T ~ M/R is high enough for nuclear reactions to achieve Thermal Equilibrium

Thermal equilibrium $$L_{radiant} = \int_0^R 4 \cdot \pi \cdot r^2 \cdot \rho \cdot \varepsilon \, dr$$

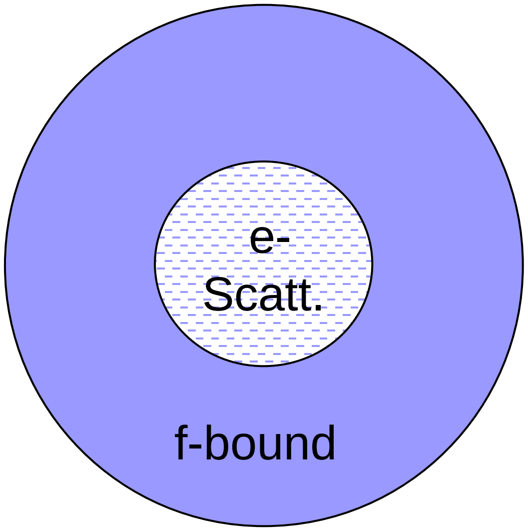
- Timescale? Kelvin-Helmholtz
  - ~ PE/L ~1/MR
    - Sun 10 million years
    - 10 M_{sun}, 2 R_{sun}, 0.5 My
    - 30 M_{sun}, 3 R_{sun}, 0.1 My, very fast!
- For less, massive, cooler stars
  - L ~ $M^{5.5}R^{-0.5}$
    - Slightly more luminous as star contracts

Sources of opacity crucial

- For cooler stars, there is more opacity than just e-scattering
  - Exactly the same opacities as stellar atmosphere
    - Line absorption (bound-bound) not important
      - Lines block only small portion of spectrum
      - Ineffective at blocking Black Body spectrum
    - Bound-free (see lectures 9 &10)
      - Photons with energy > binding energy
      - Obviously, need atoms for this
      - H, He totally ionized above 10^5 K (Saha)
      - Last abundant atom to ionize Fe
        - z = 25
        - Totally ionized above 10^7 K

Luminosity and opacity

- Consider layers of a star
  - What layer will determine L?
  - Most resistive
    - In this case the f-bound layer
- What λ's are important?
  - Stellar interior $T \sim 10^6 - 10^7$ K
  - Peak at 5 Angstrom
  - Photon energy 2 keV
    - X-rays!



Ions important for free-bound opacity

- Ionization energy with 1 electron left
  - Hydrogenic atom
    - $E_n = z^2 E_n$(Hydrogen)
    - $\chi = z^2 13.6$ eV, ionization energy
      - i.e. 54 eV for He+ ➔ He++ + e-
    - Need $z^2 \sim 100$, $z \sim 10$
  - Heavy elements z > 10 dominate free-bound opacity in the interior
    - Example Si, z = 14
      - Si+13 ➔ Si+14 requires $14^2 13.6$ eV = 2.7 keV
        - $h\nu > 2.7$ keV, Lyman continuum
        - $h\nu > (1/4)\ 2.7$ keV = 700 eV, Balmer continuum

Elements and opacity

- Si f-b opacity important till all Si in +14 state (Saha)
  - At which point heavier elements take over
- As we go down into star, f-b from succeeding ions
  - H ➔ He ➔ CNO ➔ NeMgSi ➔ Fe
    - Take turns being dominant opacity
  - Complex average, **Kramer's** opacity
    - Slide 3 above and Fig. 9.10
- When opacity very high (low T's)
  - High |dT/dr| leads to convection