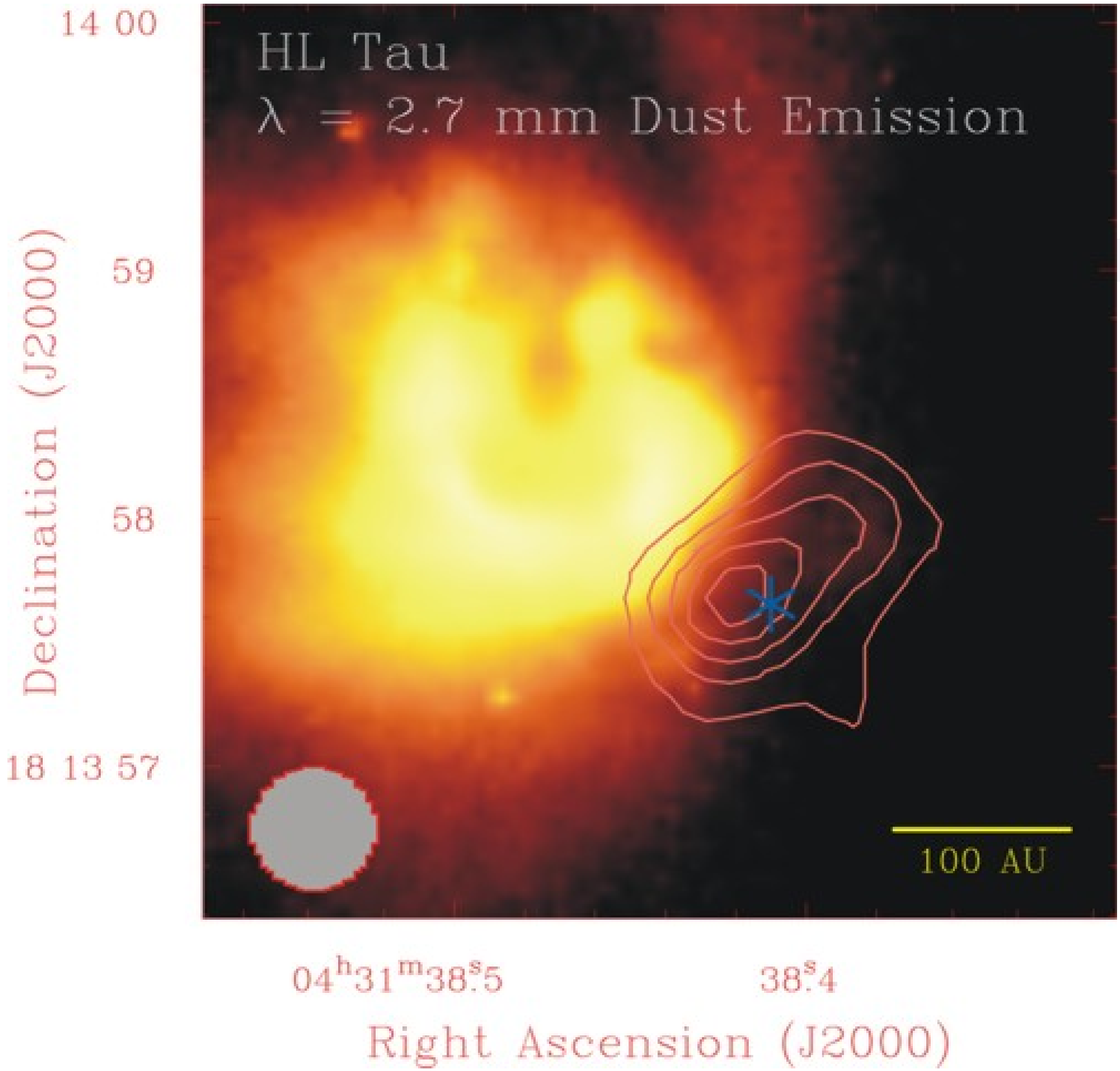
Handout 24 Star Formation

- Pictures from text
  - HL Tau
    - T Tauri star
      - Emission lines in spectrum
        - Optically thin region above photosphere
        - Either bigger or hotter than star
      - P-Cygni profile
        - Blue-shifted absorption ➔ outflow at 100’s km/s
        - Accretion engine also drives bi-polar outflows
        - Occasionally see red-shifted, infall
    - CO disk
      - Remnant from collapse of star
      - Velocities ➔ Keplerian rotation
      - Mass ~ 1-10% of star
        - From dust emission, assuming 1% mass in dust
        - CO optically thick
        - Minimum solar nebula – enough to form a solar system


HL Tau
λ = 2.7 mm Dust Emission
100 AU
14 00
59
58
18 13 57
Declination (J2000)
04h31m38.s5
38.s4
Right Ascension (J2000)

Young stellar objects

- HH 30 disk
  - Seen in silhouette
  - Star hidden in center
  - “Jets” ➔ bipolar outflow
- Disks in Orion
  - Illuminated by nebular emission
  - Sometimes see the star in center
  - Wakeup call
    - Intense radiation from nearby O-B stars can eat away disk material – evaporating disks
    - Disks dissipate (disappear) in < 10 My

Older disks (debris)

- β Pic, HR 4796
  - Only dust remains, little or no gas
    - M < 0.01% of star
  - Ages < 100 My
  - Alice Quillen models structure in disk
    - Affected by orbiting planets
      - Subtle resonance effects
  - Debris informs us about planet formation
    - Dust composition different than interstellar
      - Crystalline silicates rather than amorphous
    - Dust lifetime < age of disk
      - Radiation pressure and Poynting-Robertson drag
    - Dust replenished from larger, unseen orbiting bodies
      - Comet nuclei or Kuiper-belt objects

Complications to star formation

- Angular momentum
  - Even a tiny original spin ➔ stops collapse
    - Can only collapse parallel to spin axis
    - Formation of disk
    - Need a mechanism to transfer angular momenum
      - Magnetic fields?
      - Mechanism drives bipolar outflows
        - Carries excess angular momentum away
- Magnetic fields
  - Even tiny 0.01% ionization couples to B-field
    - Can't move perpendicular field
  - As collapse proceeds, B field increases
    - Magnetic pressure ~ B^2

Spectrum of stellar masses – “Initial Mass Function”

- Note: during initial collapse, optically thin
  - ➔ efficiently radiate away heat
    - ~ isothermal
    - Jeans mass ~ 1/sqroot(ρ) decreases
- Rotation, magnetic fields, turbulence lead to fragmentation
  - Whole spectrum of stars form
    - Most stars born in clusters
    - Most stars born in binary/multiple systems
- A “holy grail” of star formation theory is to explain the IMF – Fig. 12.9
  - While you’re at it, also explain the incidence of binaries
    - And also how many are close, how many far
      - And, by the way, explain the orbital eccentricities

Late stages of star formation

- Eventually cloud becomes opaque
  - ➔ T increases and slows collapse
    - T ~ 1500 K, dust vaporized
    - T ~ 4000 K, molecules dissociated
    - T ~ 10,000 K, H ionized
- Finally
  - Optically thick, hydrostatic equilibrium, ionized interior
    - E.g. at R = 30 Rsun
      - $\langle T \rangle \sim (1/30)\ 10^7$ K ~ $3\ 10^5$ K
  - Stellar evolution to the main sequence proceeds

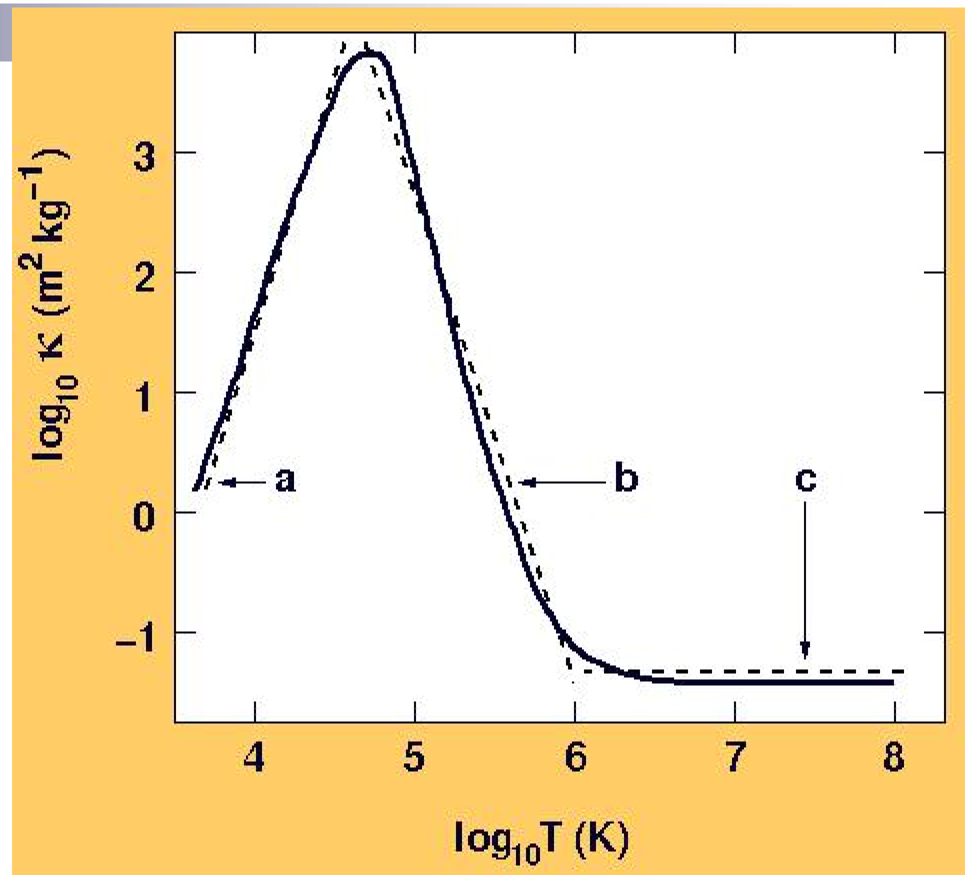
Evolution to Main Sequence

- Initially, opacity high
  - Kramers' $\kappa \sim \rho T^{-3.5}$ is large
  - Radiative |dT/dr| exceeds adiabatic
    - Convectively unstable
      - Hot air rises!
  - Interior fully convective
    - Luminosity determined by ***surface***, where it becomes radiative
      - Use $T_e = T(\tau = 2/3)$
    - Photosphere H- opacity $P(\tau = 2/3) \sim T_e^{-5.3/(1+0.7)}$
    - Interior $P(\tau = 2/3) = P_c\,(Te/Tc)^{2.5}$
      - Use virial theorem for Tc, Pc, solve for Te
  - $T_e \sim R^{0.06}$
      - Nearly vertical, Hayashi tracks on H-R diagram

T-dependence of opacity

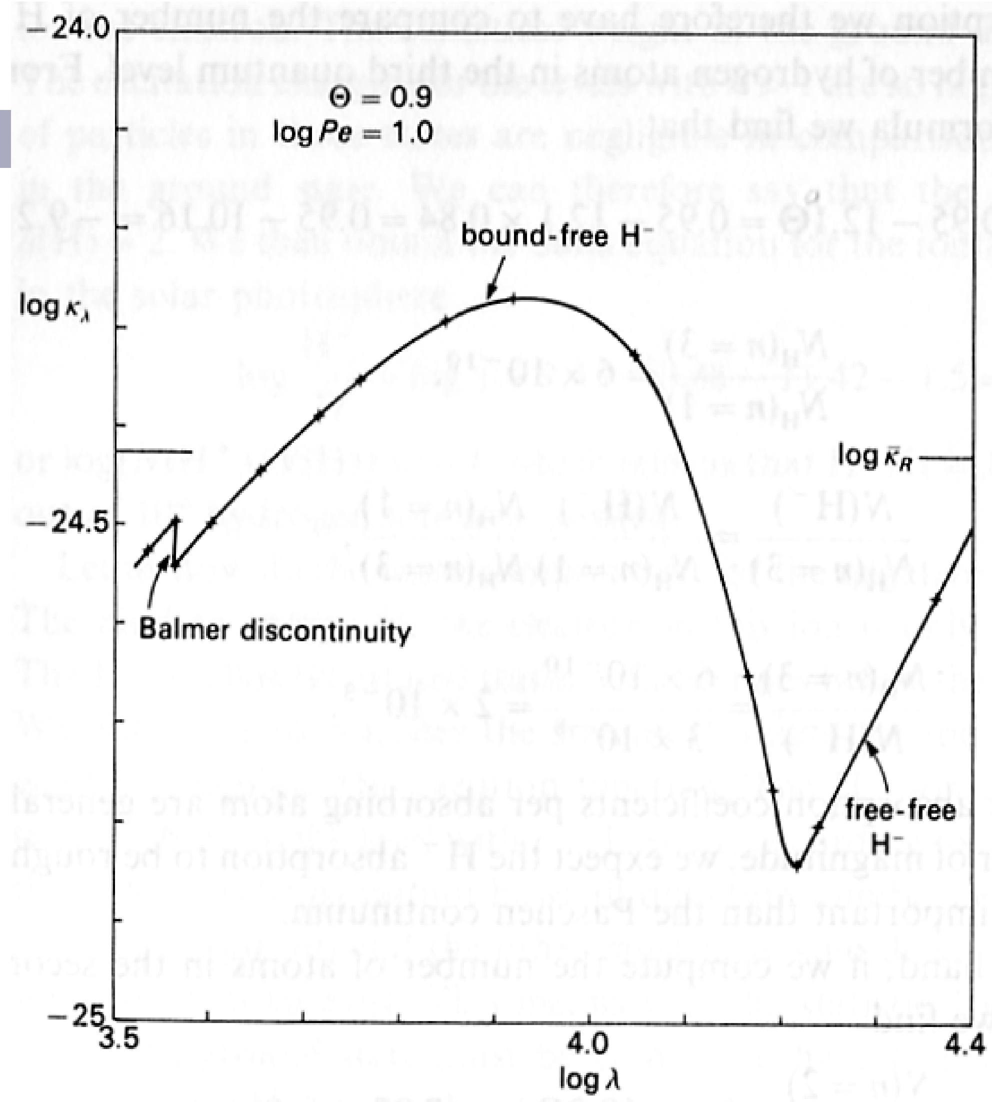
http://www.shef.ac.uk/physics/people/vdhillon/teaching/phy213/phy213_opacity_form.html

- Region a → peak
  - H- opacity
    - f-f + f-b
    - ~ T^{+4}
    - atmospheric opacity
    - → Hayashi track
- Region b
  - "metal" opacity
    - f-f + f-b
    - ~ $T^{-3.5}$
    - interior opacity
    - → rad've



H- b-f and f-f opacity

- H- (bound-free) in the visual and H- (free-free) in the IR are the principal sources of opacity in the Sun's atmosphere. For the sun, the H Balmer continuum shortward of the 3647A Balmer jump (b-f from the n=2 level) is an additional contributor.
- H- is even more dominant in cooler K and M star atmospheres.
  - opacity minimum occurs at 1.6 microns
    - Leads to flux maximum in the H-band
    - H-K color never gets very red
    - But J-H color gets very red



Evolution on H-R diagram

- Contraction along vertical, Hayashi tracks continues till opacity low enough for significant radiative region in the core develops
  - $\rho \sim M/R^3$, $T \sim M/R$, Kramers $\kappa \sim R^{0.5}$
- Now, L determined by opacity and T-gradient
  - T-gradient $|dT/dr| \sim M/R^2$ from virial theorem
  - Kramers radiative track slightly upward to left on H-R diagram
- Time scale for evolution Kelvin-Helmholtz
  - $= (1/2)|PE|/L \sim (M^2/R)/L$
  - Increasing as L and R decrease
- If hot enough, e-scattering opacity throughout interior
  - Horizontal tracks, to the left
- Eventually, ρ and T big enough for many nuclear reactions
    - $\varepsilon \sim \rho T^4$ near 15 M degrees
  - Lnuc = Lrad, “Thermal equilibrium”
- Star stops moving on H-R diagram -- it has reached the Main Sequence