I. The Sun
   a. The Visible Sun
      i. Solar Wind
      ii. Corona
      iii. Chromosphere
      iv. Photosphere
      v. Convective cells
   b. Solar Magnetic Field and Solar Activity
      i. Differential rotation
         1. magnetic field tied to charged solar gas
         2. differential rotation ties up and stresses field lines
      ii. Loops, prominences flares and coronal mass ejections from field lines breaking free
      iii. Sunspots
         1. paired points where field breaks free
         2. cooler than surroundings
         3. strong magnetic field
         4. 11 year cycle –
            a. Sunspot number varies
            b. butterfly diagram – mean sunspot latitude cycles
         5. Entire sun more active as sunspots peak
   c. The Solar Luminosity
      i. Sun emits mostly like a black body
      ii. Has been shining for billions of years – How?
   d. The Solar Interior
      i. Hydrostatic Equilibrium
         1. Implies pressure and temperature increase at smaller radii
         2. Requires central temperature of 15 million Kelvin and density of 160 times water.
         3. Core conditions permit Hydrogen fusion
      ii. Hydrogen Burning
         1. Difference between fission and fusion
         2. Net process: 4 Protons fuse into Helium
         3. Mass of Helium less than mass of four protons \( E = mc^2 \)
         4. Solar luminosity equivalent to \(5 \times 10^6 \) tons/sec of Hydrogen converted to energy
         5. Core Stability
            a. Fusion rate tied to local temperature
b. Local hot spot increases fusion $\rightarrow$ local expansion and cooling restores equilibrium.

iii. Energy Transport and Sun’s interior layers.
   1. Core $(0 < r < 0.2R_\odot)$ – Nuclear fusion, Sun’s luminosity generated here.
   2. Radiative Zone $(0.2R_\odot < r < 0.7R_\odot)$ - Slow (~$10^5$ years) photon diffusion of energy towards the surface.
   3. Convective Zone $(0.7R_\odot < r < R_\odot)$ - Rapid (~2 weeks) “boiling of material + energy to surface.

II. Measuring Physical Properties of Stars
   a. Luminosity
      i. Inverse Square Law: $\text{Luminosity} = 4\pi (\text{distance})^2 \times (\text{Brightness})$
         1. Brightness: How bright stars appear, the magnitude system
         2. Getting Intrinsic Luminosity requires measuring Distance
      ii. Parallax
         1. Compare images taken six months apart
         2. Nearby stars shift slightly with respect to distant stars
         3. Shift gives distance
   b. Temperature –
      i. Method 1 - Fit stellar spectra to black body curves
      ii. Method 2 – Level of ionization in stellar atmosphere
         1. Spectral Types
         2. OBAFGKM
   c. Radius:
      i. Assume stars are luminous black bodies: $\left(\frac{L}{L_\odot}\right) = \left(\frac{R}{R_\odot}\right)^2 \left(\frac{T}{T_\odot}\right)^4$
      ii. Distance and brightness gives Luminosity
      iii. Spectrum gives Temperature
      iv. Temperature + Luminosity gives radius.
   d. Mass
      i. At least half of all stars are binary or multiple
      ii. Types of binaries
         1. Visual
         2. Eclipsing
         3. Spectroscopic
      iii. Observing orbit
         1. Visual binaries – see orbit in time
         2. Spectroscopic binaries – Doppler shift gives orbit
      iv. Newton’s/Kepler’s Laws give mass
e. Summary of stellar properties:

Luminosity: \[ 10^{-4} < \left( \frac{L}{L_\odot} \right) < 10^6 \]

Temperature: \[ .5 < \left( \frac{T}{T_\odot} \right) < 10 \]

Radius: \[ 0.1 < \left( \frac{R}{R_\odot} \right) < 15 \]

Mass: \[ 0.08 < \left( \frac{M}{M_\odot} \right) < 100 \]

III. The Hertzsprung-Russell Diagram

a. Plots T, Color, Spectral type against Luminosity
b. Trajectories if constant Radius
c. The Main Sequence
   i. Hydrogen Burning
   ii. Hydrostatic Equilibrium
   iii. Energy Balance – Total Energy from Fusion = Luminosity
   iv. Stars ordered along the MS in Mass and age.
      1. More massive stars are hotter and brighter
      2. More massive stars live shorter MS lives
      3. MS lifetime \( \propto 1/M^3 \).
d. White Dwarfs
   i. Luminosity: \( L \approx 10^{-4} L_\odot \)
   ii. Temperature: \( T = 5,000 – 20,000 \)K
   iii. Implied Radius: \( \sim 0.01 \) of the Sun’s

e. Giants and Supergiants
   i. Luminosity: \( L \sim 10^3 – 10^5 L_\odot \)
   ii. Temperature: \( T = 3,000 – 0,000 \)K
   iii. Implied Radius: \( R \sim 10 – 100 R_\odot \)

IV. Star Clusters:

a. Open cluster.
   i. A few thousand stars
   ii. Loosely packed
   iii. Found mostly near galactic disk
b. Globular cluster.
   i. Million or more stars.
   ii. Dense
   iii. Tightly bound.
c. Cluster Ages
   i. Assume all stars form at same time
   ii. Lifetime of most massive star burning Hydrogen gives age.
   iii. Called ‘turn-off’ mass.
iv. Oldest clusters have ages of about 13 billion years

V. Stellar Birth
   a. Born in molecular clouds – cold, dense
   b. Contracting cloud gets warmer, spins up
   c. Proto-stellar disk forms
   d. Contraction ends when fusion energy = luminosity, ~50 million years
   e. A single cloud can for entire cluster
   f. Many more low mass stars form than high mass stars
   g. Brown Dwarfs
      i. Mass < 0.08 Mass of the sun
      ii. Too small to fuse Hydrogen
      iii. Collapse stopped by degeneracy pressure
      iv. Degeneracy Pressure
         1. electrons resist being squeezed together
         2. Pressure depends only on density not temperature

VI. Stellar Evolution
   a. Low Mass stars like the Sun
      i. Core Hydrogen depleted: Fusion stops.
      ii. Core cools: contracts.
      iii. Gravitational energy released: Envelope expands (Red Giant).
      iv. Hydrogen Shell Ignites
      v. Core ignites Helium: core contraction stops, envelope contracts.
      vi. Core Helium depleted.
      vii. Core contracts: envelope expands
      viii. Envelope detaches and expands away from star: planetary nebula
      ix. Core continues cooling as White Dwarf
   b. High Mass Stars
      i. Evolution starts like low mass star
      ii. High mass stars burn Hydrogen with C-N-O cycle.
      iii. Star go to supergiant rather than giant region of HR diagram
      iv. From carbon core fusion proceeds by He capture
      v. Heavier elements produced until Iron core forms
      vi. Iron burning cools star.
      vii. Collapsing core pressure “squeezes” electron into protons to make neutrons
      viii. Degenerate core pressure disappears.
      ix. Core undergoes rapid collapse
       x. Stellar envelope explodes – supernova
       xi. Elements heavier than iron produced in supernova shock
   c. Evolution of composition in the Universe
      i. Massive stars produce heavy elements
      ii. Supernovae and stellar winds seed clouds with heavy elements
      iii. Next stellar generation has more heavy elements

VII. Supernova Remnants
   a. Neutron Stars
      i. Sea of neutrons left after electrons are crushed into protons.
ii. Supported by degenerate neutron pressure  
iii. Spin rapidly  
iv. High magnetic field  
v. Observed as pulsars  
  1. regular pulses  
  2. associated with supernova remnants  
  3. lighthouse effect  
b. Black Holes  
i. Neutron degenerate pressure not enough for mass > 3 solar masses  
ii. Collapse continues till escape velocity exceeds speed of light  
iii. No particles can escape  
iv. Event Horizon – radius where falling particle can last communicate with outside world.  
v. To make a black hole \( R = 3km \left( \frac{M}{M_\odot} \right) \), Schwarzschild radius  
vi. Observed as X-ray sources  
  1. BH in binary system has mass fall on to it  
  2. Particles accelerating into BH gives off X-rays  

vii. The core of the Milky Way galaxy  
  1. Bright radio/IR source at galactic center  
  2. Many young, bright stars orbit core  
  3. Orbits give a mass of ~ 4 million solar masses in a region the size of the solar system.  
  4. Super-massive black hole