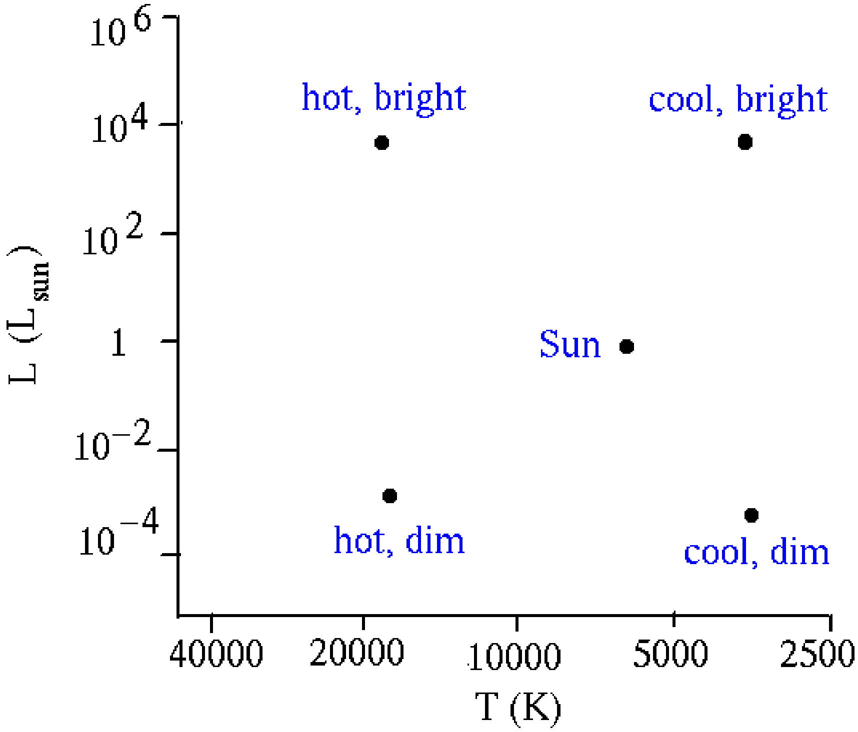
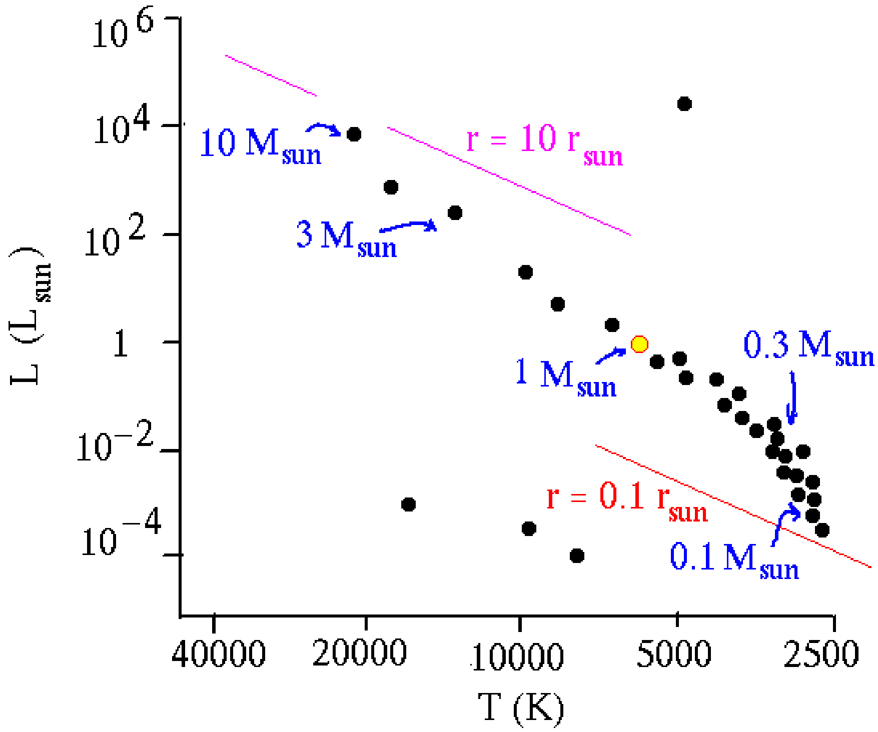
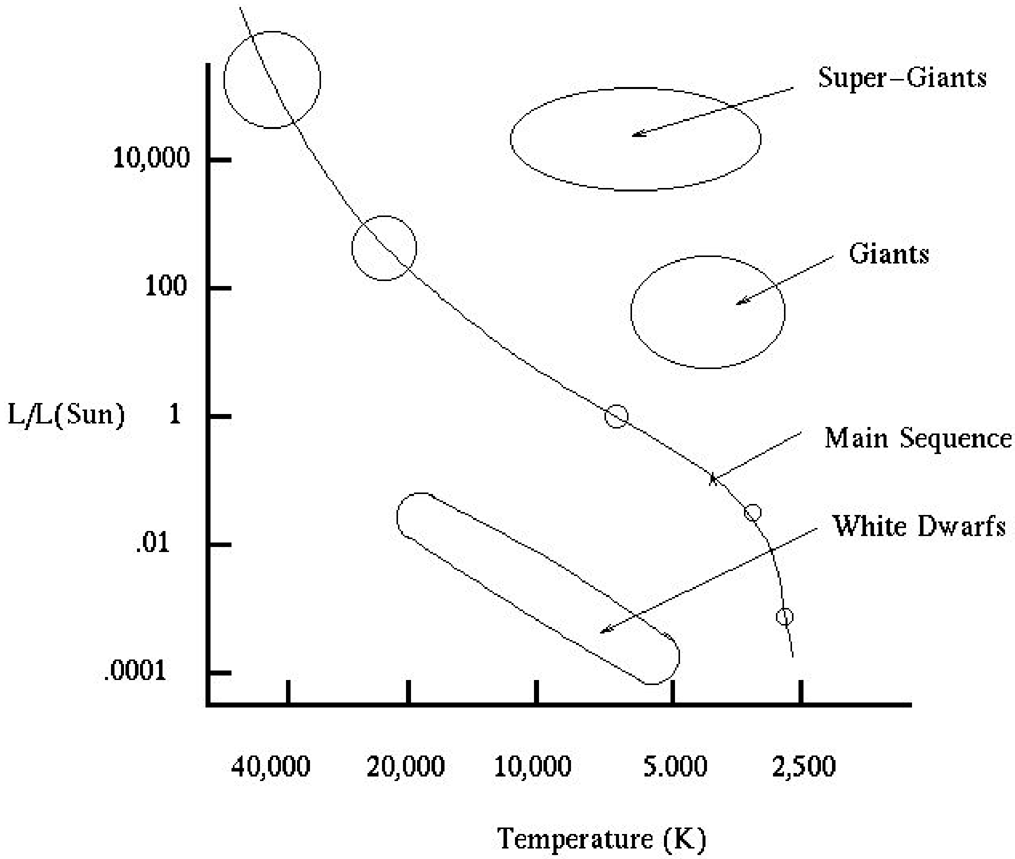
Hertzsprung Russell Diagram







Temperature, size and luminosity

We know that for objects that are approximately blackbodies

- Hotter things are brighter.
  - Energy radiated per unit time per unit area is proportional to T^4,
  - so bigger T means more energy radiated
- Bigger things are brighter.
  - so bigger surface area means more energy radiated.

Putting this together, we have

$$L = 4\pi r^2 \sigma T^4$$

[Taken from http://zebu.uoregon.edu/~soper/Stars/hrdiagram.html]

C. Explosive Nucleosynthesis – Nova Explosions – Massive Stars

1. Carbon and Oxygen Burning: C/O core

   a. Conditions
   $$\left\{ \begin{array}{l} \rho \sim 5 \times 10^5 \text{ g/cm}^3 \\ T \sim 5 \times 10^8 \text{ K} \end{array} \right\}$$

   b. Heavy-ion Reactions:
   $$\left\{ \begin{array}{l} {}^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^{4}He \\ {}^{12}C + {}^{16}O \rightarrow {}^{24}Mg + {}^{4}He \\ {}^{16}O + {}^{16}O \rightarrow {}^{28}Si + {}^{4}He \end{array} \right\} \quad Q = +$$

   c. Reaction Rates now rapid – all strong, two-body interactions. Nuclide mixture becomes richer ; secondary reactions from odd-Z nuclei – less probable since must be made from even-Z nuclei.

   e.g., $${}^{12}C({}^{16}O, n){}^{27}Si \xrightarrow{\beta+} {}^{27}Al$$
   $${}^{24}Mg(n, \gamma){}^{25}Mg$$
   } form neighboring nuclei; accounts for odd-even abundances

2. Silicon Burning: e-process [e for equilibrium]

   a. Conditions:
   $\rho \sim 10^6$ g/cm^3

   $T \sim 5 \times 10^9$ K

   b. Reactions: (α, γ) and (γ, α) in "equilibrium" (i.e., 4n nuclei)

   $${}^{28}Si(\gamma, \alpha){}^{24}Mg: \ {}^{28}_{14}Si + {}^{4}He \rightleftharpoons {}^{32}_{16}S + {}^{4}He \underset{\gamma}{\overset{\alpha}{\rightleftharpoons}} {}^{36}_{18}Ar \rightleftharpoons {}^{40}Ca \dashrightarrow {}^{56}_{28}Ni$$

   All reactions exothermic: $Q = +$

   c. Reactions are in "equilibrium", but material is processed towards ${}^{56}_{28}Ni$

   d. Net Product: $${}^{56}_{28}Ni \xrightarrow{EC} {}^{56}_{27}Co \xrightarrow{EC/\beta+} \boxed{{}^{56}Fe}$$ Most stable nucleus in nature

   e. Schematic Diagram of Burning Envelopes

f. Beyond ^{56}Fe

(1) Q-values less/not favorable

(2) Coulomb Barriers increase

g. RESULT

Gravity overcomes thermal pressure; leads to destabilization of core $\Rightarrow$ IMPLOSION – gravitational collapse.

D. Supernova Explosions: r-process [r = rapid]

1. Core Conditions = $\left\{ \begin{array}{l} \rho \sim 10^8 \text{ g/cm}^3 \\ T \sim 6 \times 10^{10} \text{ K} \end{array} \right\}$

2. Collapse Time: 10-1000 seconds

3. Rebound: **EXPLOSION** (compression/decompression cycle) i.e., sudden heating from compression triggers shock wave in stars 1987a ; Crab Nebula (1054 AD)

4. Nuclear Reactions – Two Zones

a. Core (highest temperature)

(1) Heat bath dissolves nuclei

$$^{56}_{26}\text{Fe} + \gamma \xrightarrow{\sim 124 \text{ MeV}} 13\ ^4\text{He} + 4\,^1_n$$

$$\hookrightarrow 26\ ^1\text{H} + 26\ ^1\text{n}$$

$$^1\text{H} + e^- \rightarrow n + \nu$$

i.e., copious neutron production

(2) Implosion may lead to neutron star formation

i.e., a nuclear gas $\rightarrow$ liquid phase transition

$\rho \gtrsim 5 \times 10^{14}$ g/cm^3 ; pulsars

b. Envelope around Core: Heavy Element Synthesis

Cooler environment permeated by neutrons from core

(1) Rapid neutron capture in ^{56}Fe seed nuclei

$\therefore$ A increases

$$\left\{ {}^{56}Fe \xrightarrow{n} {}^{57}Fe \xrightarrow{n} {}^{58}Fe \xrightarrow{etc.} {}^{69}Fe \right\}$$ (Neutron Drip Line

$<\tau_{capture}> \sim 10^{-6}$ s 2T > Bn

(2) Negatron Decay of neutron-rich Products ; $t_\beta > 10^{-3}$ s

∴ Z increases

$$\left\{ {}^{59}_{26}Fe \xrightarrow{\beta^-} {}^{69}_{27}Co + \beta^- + \bar{\nu} \right.$$

$$\left. \xrightarrow{n} {}^{70}_{27}Co \xrightarrow{n} {}^{71}_{27}Co \xrightarrow{\beta^-} {}^{71}_{28}Ni + \beta^- + \bar{\nu}, \text{ etc.} \right\}$$

(3) "Laboratory" Analogue: Thermonuclear explosions

$_{61}$Pm, $_{99}$Es, $_{100}$Fm, and $_{101}$Md all discovered in nuclear bomb debris.

c. Secondary Reactions – rp process

As ejected material from core passes through hydrogen envelope, following type of reactions occur:

$${}^{28}Si\,({}^{1}H,\gamma){}^{29}P \overset{\beta^-}{\dashrightarrow} {}^{29}Si\ ;\ {}^{110}_{48}Cd({}^{1}H,\gamma){}^{111}_{49}In({}^{1}H,\gamma){}^{112}_{50}Sn$$

i.e., Isotopic abundances of all elements are enriched, **BUT** in much smaller yields than primary isotopes

d. Terminal Step

Nuclear Fission @ Z ~ 90-92, A ~ 270

(n,f) reactions terminate chain; mass buildup ceases and material simply cycles: $^{56}Fe \xrightarrow{n}$ heavy elements $\xrightarrow{f}$ fission products $\xrightarrow{n}$

E. Stellar Evolution: A Cyclic Process

1. Sun: Must be at least a second-generation star;
   Evidence: atomic spectra of heavy elements observed in photosphere.

2. Later-generation Stars: Richer mix of nuclei
   adds to abundances of odd Z and odd A isotopes

3. s-process [s = slow]
   Later generation Red Giant Stars
   Sequence of neutron captures and negatron decays on much longer time scale
   Evidence: $_{43}$Tc and $_{61}$Pm atomic spectra in these stars

   a. Neutron Production: **A increases**

      Secondary reactions on odd-A products from previous cycles
      $^{13}C(\alpha,n)^{16}O$; $^{17}O(\alpha,n)^{20}Ne$; $^{21}Ne(\alpha,n)^{24}Mg$

   b. Time scale: $\langle t \rangle_{capture} \simeq 10^3$ y
      Due to long lifetimes of Red Giants ($10^7 - 10^8$ y) and low abundances of ^{13}C, ^{17}O, & ^{21}Ne, neutrons are produced SLOWLY

   c. Negatron Decay: **Z increases**

$$^{56}_{26}\text{Fe} + {}^{1}\text{n} \longrightarrow {}^{57}_{26}\text{Fe} \xrightarrow{n} {}^{58}_{26}\text{Fe} \xrightarrow{n} {}^{59}_{26}\text{Fe}\ (45\ \text{d}, \beta^-)$$

$$^{59}_{26}\text{Fe} \longrightarrow {}^{59}_{27}\text{Co} + \beta^- + \bar{\nu}$$

   Low capture rate means that negatron decay usually occurs BEFORE another neutron can be captured (unless t_{β^-} long)

   d. s-process follows the valley of β^- stability
      r-process follows a path far to the neutron excess side of β stability

e. Terminal Nucleus: $^{209}_{83}Bi$

$$^{209}_{83}Bi + {}^{1}n \longrightarrow {}^{210}_{83}Bi \xrightarrow{\beta^-} {}^{210}_{84}Po \xrightarrow[138\ d]{\alpha} {}^{206}Pb \xrightarrow{n} {}^{207}Po \dashrightarrow {}^{209}Bi$$

f. Summary: s-process makes medium-mass isotopes of an element
r-process makes heaviest isotopes of an element
rp-process – makes lightest isotopes

III. GCR + ISM Nucleosynthesis: LiBeB

{ $^{6}_{3}Li$, $^{9}_{4}Be$ and $^{10,11}_{5}B$ only elements not accounted for }
GCR = Galactic Cosmic Rays
ISM = Interstellar Medium

A. Mechanism: Evidence – GCR abundances (much richer in LiBeB)

Need a cold environment for LiBeB to survive due to weak binding

∗Scenario:∗

1. $\rightarrow$ GCR $\rightarrow$ ISM $\rightarrow$ $\Rightarrow$ $^{6,7}_{3}Li$, $^{9}_{4}Be$, $^{10,11}_{5}Li$
   (^{1}H, ^{4}He, CNO …) (^{1}H, ^{4}He, CNO …)

2. Abundances of both GCR and ISM well-measured

3. Reaction cross sections provide test of model

B. Fit to model is quantitative (except for ^{7}Li -- ? Big Bang)

C. Permits estimate of baryon density of universe

D. Experimentalists conclusion: **not enough mass present in the universe to reverse expansion; ∴ Universe will expand forever**

E. Theorists: Inflation theory (creates inhomogeneous Universe) **says there should be ~10× more mass than we measure; ν mass; dark matter, etc.**