Summary: Physical Properties of Stars

**Photospheric (“Surface”) Temperatures**
3,000°K (Red M stars) to 40,000°K (Blue-White O stars)

**Luminosities**
Main Sequence: $L_{M5V} \approx 10^{-2} L_{\odot}$ to $L_{O5V} \approx 10^6 L_{\odot}$
Also red supergiants at $10^5 L_{\odot}$ to white dwarfs at $10^{-4} L_{\odot}$.

**Stellar Radii**
Main Sequence: $R \approx 0.3$ to $18 R_{\odot}$ (M5V to O5V)
Giants & Supergiants: $R \approx 1,000$ to $18 R_{\odot}$ (M5V to O5V)
White Dwarfs, Neutron Stars: $R_{wd} \approx 10^{-2} R_{\odot}$ & $R_{ns} \approx 10^{-5} R_{\odot}$

**Stellar Masses**
$M \approx 0.1 M_{\odot}$ to $M \approx 30 M_{\odot}$
Also white dwarfs at $0.6$ to $1.2 M_{\odot}$

The Mass-Luminosity Relation for main sequence stars:
$L_{\text{Star}}/L_{\odot} \approx [M_{\text{Star}}/M_{\odot}]^{3.5}$
Some Empirical Relationships Among Stellar Properties

Surface Temperature - Spectral Type - Star Color
(4,000°K to 3,000°K)  (OBAFGKMN)  (Blue to Red)

Surface Temperature - Luminosity - Radius
(The Hertzsprung Russell Diagram)

The Mass-Luminosity Relation for main sequence stars:
\[ \frac{L_{\text{Star}}}{L_{\text{Sun}}} \approx \left( \frac{M_{\text{Star}}}{M_{\text{Sun}}} \right)^{3.5} \]
What Makes the Stars Shine?

Estimating Stellar Lifetimes

Assumptions

1. All stars “run” on the same basic process.
   ... whatever that may be.
   (The “efficiency” is the same for all stars)

2. A star’s fuel reserves are contained within the star
   ... and proportional to the star’s initial mass.
   (Stars are not “refueled” from external sources.)

3. A star’s energy production rate is given by its luminosity
   ... with no other sources of energy loss.
   (The luminous output is the only energy output.)

Remember, these are assumptions.............
Estimating Stellar Lifetimes

Then stellar lifetimes $\tau_{\text{star}}$ are proportional to $M_{\text{star}}/L_{\text{star}}$ or

$$\frac{\tau_{\text{star}}}{\tau_{\text{Sun}}} = \frac{M_{\text{star}}}{L_{\text{star}}} \quad \text{(solar units)}$$

It is observed that, for main sequence stars

$$L_{\text{star}} = M_{\text{star}}^{3.5} \quad \text{(solar units)}$$

(This is the “Mass-Luminosity Relation”)

So that

$$\frac{\tau_{\text{star}}}{\tau_{\text{Sun}}} = M_{\text{star}}^{-2.5} \quad \text{(solar units)}$$

Implications:

Low-mass stars are long-lived, high-mass stars short-lived.

Examples:

\begin{align*}
M_{\text{star}} &= 10 \, M_{\text{Sun}} \quad \text{gives} \quad \tau_{\text{star}} = 0.003 \, \tau_{\text{Sun}} \\
M_{\text{star}} &= 0.1 \, M_{\text{Sun}} \quad \text{gives} \quad \tau_{\text{star}} = 0.316 \, \tau_{\text{Sun}}
\end{align*}

But what is $\tau_{\text{Sun}}$?
What Makes the Stars Shine?
Consider the Sun:

Estimating the Energy Production Requirement

The Sun’s Luminosity is $L_{\text{Sun}} = 3.8 \times 10^{26}$ watts

The Sun’s Lifetime is $\tau_{\text{Sun}} > 1.4 \times 10^{17}$ seconds
(i.e., at least 4.5 Billion Years)

The energy produced is $E_{\text{Sun}} = L_{\text{Sun}} \tau_{\text{Sun}} > 5.5 \times 10^{43}$ joules
(at least $1.5 \times 10^{37}$ kilowatt-hours)

Question:
What processes might be able to produce at least this amount of energy from, at most
$1 \ M_{\text{Sun}} = 2 \times 10^{30}$ kilograms
of fuel?
What Makes the Sun Shine?

**POSSIBILITIES**

**Residual Heat?** \[ \tau_{\text{Sun}} \approx M c_v / L \] \[ \tau_{\text{Sun}} \approx 20,000 \ \text{yr} \] (\( c_v \) = Specific heat, \( T \) = Temperature)  

**Chemical Reactions?** \[ \tau_{\text{Sun}} \approx M \varepsilon_c / L \] \[ \tau_{\text{Sun}} \approx 5,000 \ \text{yr} \] (\( \varepsilon_c \) = Specific energy production rate; Assume \( \text{H} + \text{F} \rightarrow \text{HF} \))  

**Gravitational Energy?** \[ \tau_{\text{Sun}} \approx G M / R L \] \[ \tau_{\text{Sun}} \approx 5 \times 10^7 \ \text{yr} \] (\( G \) = Gravity Constant; Assume contraction to radius \( R \)).

**Nuclear Fission?** \[ \tau_{\text{Sun}} \approx M \varepsilon_u / L \] \[ \tau_{\text{Sun}} \approx 1 \times 10^{10} \ \text{yr} \] (\( \varepsilon_u \) = Specific energy production rate; Assume \( \text{U} \rightarrow \text{Pb} \)).

**Nuclear Fusion** \[ \tau_{\text{Sun}} \approx M \varepsilon_N / L \] \[ \tau_{\text{Sun}} \approx 1 \times 10^{11} \ \text{yr} \] (\( \varepsilon_N \) = Specific energy production rate; Assume \( 4\text{H} \rightarrow \text{He} \)).

**Fusion: Historical Motivation**

Einstein’s Theory of Relativity (\( E = M c^2 \))
Atomic Masses (H & He), the Solar Composition (H & He)
Nuclear Reactions

Nomenclature
Atomic Number (Z) → $^{6}\text{C}^{12}$ ← Atomic Weight (A)
Chemical Symbol ↑ (C for Carbon)

Atomic Number = Number of Protons (+)
(Identifies the element: 6 → “Carbon”)
Atomic Weight = Number of Protons (+) plus Neutrons (o)
(Identifies the isotope: “Carbon-12”)

Nuclear Reaction Examples

Nuclear Fusion: $^{92}\text{U}^{235} + ^{0}\text{n}^{1} \rightarrow ^{92}\text{U}^{236}$
neutron ↑

Nuclear Fission: $^{92}\text{U}^{236} \rightarrow ^{54}\text{Xe}^{140} + ^{38}\text{Sr}^{94} + ^{0}\text{n}^{1} + ^{0}\text{n}^{1} + \gamma$
gamma ray ↑

The Simplest Fusion Reaction:
$^{1}\text{H}^{1} + ^{1}\text{H}^{1} \rightarrow ^{1}\text{H}^{2} + ^{0}\text{e}^{+} + \nu$ ← a “neutrino”
“deuterium” ↑  ↑ a “positron”

also Matter-Antimatter Annihilation:
$^{0}\text{e}^{-} + ^{0}\text{e}^{+} \rightarrow \gamma$
electron ↑ ↑ positron