How long would the Sun shine?

- The Sun needs fuel to shine.
  - The Sun shines by consuming the fuel -- it generates energy from the fuel.
- The lifetime of the Sun is determined by
  - How fast the Sun consumes the fuel, and
  - How much fuel the Sun contains.
- How fast does the Sun consume the fuel?
  - Energy radiated per second is called the "*luminosity*", which is in units of watts.
  - The solar luminosity is about 3.8×10^{26} Watts.
    - Watts = Joules per second
    - Compare it with a light bulb!
- What is the fuel??

Fuel = Gravitational Energy?

- The mass of the Sun is $M = 2 \times 10^{30}$ kg.
  - The amount of the fuel should be related to the amount of mass.
- Gravity can generate energy.
  - A falling body acquires velocity from gravity.
  - Gravitational energy = $(3/5)GM^2/R$
  - The radius of the Sun: R = 700 million m
  - Gravitational energy of the Sun = 2.3×10^{41} Joules.
- How long could the Sun shine on gravitational energy?
  - Lifetime = (Amount of Fuel)/(How Fast the Fuel is Consumed)
  - Lifetime = (2.3×10^{41} Joules)/(3.8×10^{26} Joules per second) = 0.6×10^{15} seconds.
  - Therefore, the Sun lasts for **20 million years** (Helmholtz in 1854; Kelvin in 1887), if gravity is the fuel.

Fuel = Nuclear Energy

- Einstein's Energy Formula: $E=Mc^2$
  - The mass itself can be the source of energy.
- If the Sun could convert *all* of its mass into energy by $E=Mc^2$…
  - Mass energy = 1.8×10^{47} Joules.
    - Compare it with the gravitational energy, 2.3×10^{41} Joules, which can keep the Sun shining for 20 million years.
  - The Sun would shine for about **15 trillion years** on mass energy!
- How can the mass be converted into energy?
  - Nuclear reaction
  - Nuclear reaction in the Sun can convert ~0.07% of the mass into energy.
- Therefore, the Sun shines for…
  - 15 trillion years x 0.0007 ~ **10 billion years**

Burning Hydrogen: p-p chain

- $^1H + ^1H \rightarrow ^2H + e^+ + \nu_e$
- $^2H + ^1H \rightarrow ^3He + \gamma$
- $^3He + ^3He \rightarrow ^4He + ^1H + ^1H$
  - ^1H: proton, ^2H: deuteron
  - ^3He: Helium-3, ^4He: Helium-4
  - e^+: positron, ν_e: neutrino, γ: gamma ray
- In total, four protons are fused into one helium-4 and produce energy:
  - $^1H + ^1H + ^1H + ^1H \rightarrow ^4He$ + "binding energy"
  - One proton weighs 1.6726×10^{-27} kg
  - One helium-4 weighs 6.643×10^{-27} kg
  - Four protons minus one helium = 4.7×10^{-29} kg -> energy
    - This is 0.7% of the original mass of four protons.

How Hot is the Sun?

- Hydrogen gas is pulled inward by gravity.
- Hydrogen Gas is pushed outward by pressure.
  - Nuclear energy heats up gas -> high pressure
  - Pressure = k_B x (number density of hydrogen) x (temperature)
  - Pressure is the highest at the center and decreases at larger distances.
- "Hydrostatic equilibrium" = "Pressure force balances gravitational force"
  - Gravity = GM^2/R^2
  - Pressure = $k_B nT$
  - Calculations show that temperature should be ~**20 million K**
  - High temperature is necessary to balance enormous gravity.

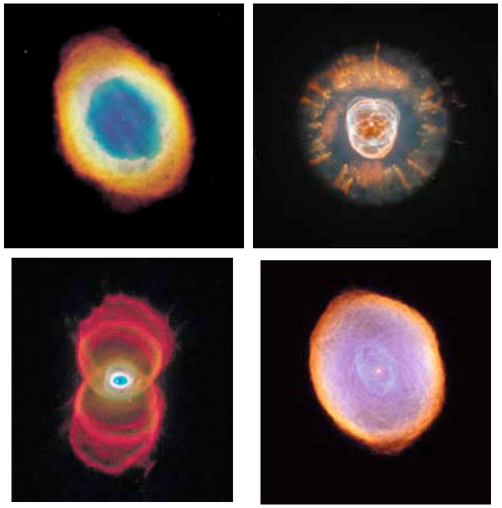
Core is Hotter, Surface is Cooler

- Core (0-0.25 R_{solar}): ~15 million K
  - Energy is produced by hydrogen burning
- Radiative zone (0.25-0.70 R_{solar}): 2 to 8 million K
  - Energy is carried by radiation (photons) up to near the surface of the Sun
  - Photons frequently scattered by electrons (random walk)
- Convective zone (0.70-1 R_{solar}): < 2 million K
  - Photons are absorbed by atoms near the surface; unable to carry energy
  - Energy is then carried by "convection" (e.g., boiled water)
- Surface: 5,800 K
  - It takes about a million years from the core to the surface.

Fate of the Sun

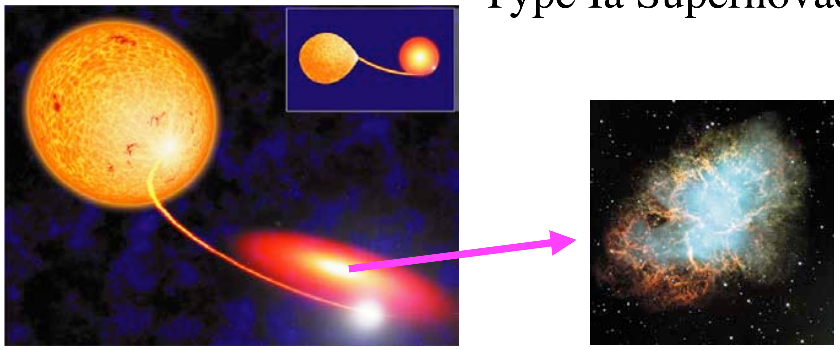
- The Sun will eventually run out of fuel…
  - The Sun is about 5 billion years old.
  - Hydrogen burning can keep the Sun shining for about 10 billion years.
- What would happen after that?
  - The Sun will find another source of fuel: **Helium**
- When hydrogen nuclei are exhausted, the Sun begins to contract, getting hotter.
- When temperature in the core increases to ~100 million K, helium begins to burn, generating nuclear energy again. The surface of the star expands.
  - $^4He + ^4He + ^4He + ^4He \rightarrow ^{12}C$ + (binding energy)
- When helium nuclei are exhausted, the star wants to burn carbon, but a low-mass star can't burn it…
  - $^{12}C + ^4He \rightarrow ^{16}O$ + (binding energy); this reaction requires ~600 million K! So, a low-mass star becomes a carbon star.

White Dwarfs and Planetary Nebulae



- Expanding gas gets **ionized** by radiation from the central core
- The carbon core became a "White Dwarf"
  - Supported by "*degeneracy pressure*"
- The expanding gas
  - Planetary nebula

Type Ia Supernovae



- If the W.D. has a companion star, mass from the companion accretes on the W.D., increasing mass.
- At some point ($M>1.4M_{solar}$), carbon begins to burn!
  - The “carbon bomb” disrupts the W.D. completely
  - This type of supernova is called the “Type Ia”, and plays a very important role in cosmology

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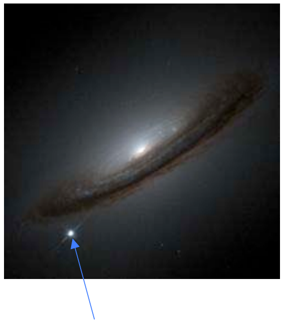
Importance of Type Ia in Cosmology



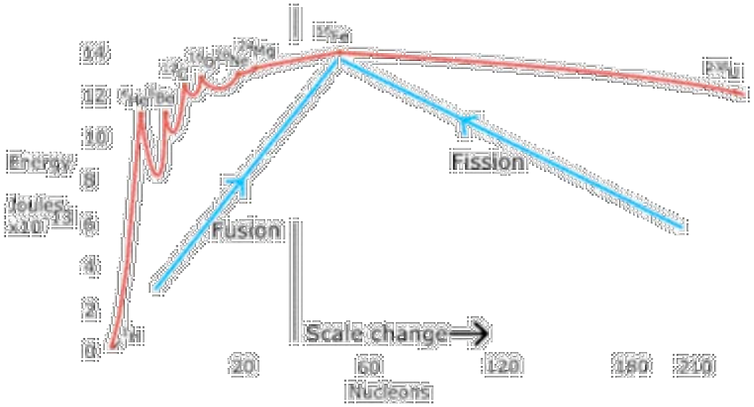
Type Ia supernova

- We can estimate distances to Type Ia supernovae fairly accurately.
  - Because they all explode at the same mass ($\sim 1.44M_{solar}$), their luminosity is roughly the same for all Type Ia.
    - We measure their brightness.
    - We know their luminosity.
    - Luminosity-brightness relation gives distances.
- ***Distance-redshift relation*** is one of the fundamental cosmological probes.
- How do we find Type Ia?
  - No hydrogen line should be seen for Type Ia

What about Type II?

- $M>2M_{solar}$
  - More mass, more gravity -> More pressure, higher temperature
  - Hydrogen and helium are much more rapidly consumed (~a few 100,000 years or less vs billions of years)
  - Then, carbon does fuse!! (E.g., $^{12}C + ^{4}He \rightarrow ^{16}O$)
  - Heavier elements are also burned one after another.
    - E.g., $^{16}O + ^{4}He \rightarrow ^{20}Ne$, $^{20}Ne + ^{4}He \rightarrow ^{24}Mg$
    - E.g., $^{12}C + ^{16}O \rightarrow ^{28}Si$, $^{28}Si + ^{28}Si \rightarrow$ **^{56}Fe**
  - **Iron (^{56}Fe) is the terminal**: no more energy gain by fusion.
  - The core keeps shrinking… Gravitational force is not balanced by thermal pressure… Where would the gravitational energy go…
  - *Type II Supernova*!! (Hydrogen lines should be seen.)
- Intermediate mass stars ($8M_{solar}>M>2M_{solar}$)
  - The core becomes a *neutron star* (~10km across; rapidly rotating)
- Very high mass stars ($M>8M_{solar}$)
  - The core collapses into a *black hole*

Binding Energy Diagram



- Fusion generates energy until it reaches the “iron peak”.
- Fission generates energy by destroying nuclei heavier than iron.

Life and Low- and High-mass Stars

- Low-mass stars are necessary for life because…
  - Planets can form around low mass stars
  - Stars live long enough (~billions of years) for complex form of life to emerge
- High-mass stars are necessary for life because…
  - Low-mass stars alone cannot produce important heavy elements such as carbon, oxygen, nitrogen, etc.
  - High-mass stars can create heavy elements by fusion, and eject the created elements into space by Type II supernova explosion.
- Life is not possible without both!