The Sun’ Energy Production Mechanism &
the Earth — Sun Connection

Astronomy 104 ; Lecture 1

April 5, 2004 Guest Lecture
by
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The Sun’s Energy Source?

Energy Equilibrium - “Energy lost = Energy produced”

So, what are energy sources for Sun’s luminosity?

1. Chemical, \( C + O_2 \rightarrow CO_2 \)
   Adequate for perhaps 10,000 years

2. Gravity, \( E = GM / \Delta R \)
   Adequate for perhaps 200,000 years

3. Nuclear

\[ E = \Delta m \ C^2 \]

Speed of light (3 x 10^8 m/sec) Squared

Adequate for 10 x 10^9 (billion) years or more
The Sun’s Energy Source!

Thermonuclear Hydrogen Fusion

\[ 4 \ H \rightarrow \ He \]

\[ 4 \ H = 4 \times 1.673 \times 10^{-27} \ kg = 6.693 \times 10^{-27} \ kg \quad \text{Fuel Mass} \]

\[ - \ 1 \ He = 6.645 \times 10^{-27} \ kg \quad \text{Left Over Mass} \]

\[ 0.048 \times 10^{-27} \ kg \quad \text{Change, } \Delta m \]

\[ (0.048 \times 10^{-27} \ kg) \times (3 \times 10^8 \ m/s)^2 = 4.3 \times 10^{-12} \ \text{joules} \]

That’s from \( 6.7 \times 10^{-27} \ \text{kg} \) of fuel,

So from 1 kg we get \( E = 6.4 \times 10^{14} \ \text{Joules} \)

The Mass of the Sun is, \( M = 2 \times 10^{30} \ \text{kg} \)

The Sun’s Energy Output (Luminosity) \( L = 3.9 \times 10^{26} \ \text{Joules s}^{-1} \)

So the Sun can do what it’s doing now for a time, \( \tau \)

\[ \tau = \frac{M \times E}{L} = \frac{2 \times 10^{30} \ \text{kg} \times 6.4 \times 10^{14} \ \text{J kg}^{-1}}{3.9 \times 10^{26} \ \text{J s}^{-1}} = 3.3 \times 10^{18} \ \text{s} \]

\[ \tau = 10^{11} \ \text{years} \]
Overcoming Electrostatic Repulsion

Why “Thermonuclear”?
Positive charges Repel One another Very Strongly

- Requires both High Density (so it happens often)
- Especially Very High Speed i.e. VERY HIGH TEMPERATURE

At low speeds, electromagnetic repulsion prevents the collision of nuclei.

At high speeds, nuclei come close enough for the strong force to bind them together.
The Proton – Proton Chain
Thermonuclear Hydrogen Fusion      \( 4 \, H \rightarrow He \)

2 Protons
i.e. Hydrogen Nuclei

Deuterium

Positron

Neutrino

Helium 3

Do Steps 1 & 2 A second time

Helium 4

\[ e^+ + e^- \rightarrow 2\gamma \]

\[ H + H \rightarrow D + \nu + e^+ \]

\[ He + He \rightarrow He + 2\,H \]
"I am at last convinced that the spots are objects close to the surface of the solar globe ... also that they are carried around the Sun by its rotation"

---- Galileo 1613, *Historia e Dimostrazioni intorno alle Macchie Solari*

Normal Photosphere Temperature = 5700 K
Sun Spot “Umbra” Temperature = 4200 K

Granulation
- Size ~ 1000 km
- $\Delta T \sim 150$ K
- Life time ~ 10 min
- Tops of Convection Cells
Sun Spot Number vs. Time

The graph shows the number of sunspots over time from 1900 to 2000. The number of sunspots fluctuates significantly, with peaks occurring at regular intervals. The y-axis represents the number of sunspots, ranging from 0 to 200, while the x-axis represents the years from 1900 to 2000.
Sun Spot Number v Time

George E. Hale
Spot \textbf{Magnetic} Fields
1908

Hale & Nicholson
Systematics of \textbf{Bipolar} Magnetic Regions
1925

The Maunder Diagram

"Maunder Minima"
Particularly Severe Winters
Spectrograph Slit Over Sun Spot
Coronal Loops
Outflow (Solar Wind)

$V \sim 500 \text{ km s}^{-1}$

$N_{\text{electron}} = N_{\text{proton}} \sim 1 \text{ cm}^3 \quad \text{(at 1 a.u.)}$

$T \sim 10^6 \text{ K}$
Solar Activity, Some Facts & Figures

- **Flares**
  - Release of up to $10^{23}$ Joules in 10 – 100 minutes
  - Radio & X-ray Bursts, seen immediately
    - Correspond to gas at $T \sim 10^7$ K
  - High particle ($^1$H & e$^-$) Flux @ Earth, 1 – 5 days later
- **Frequency**
  - at Solar Max, 1500 yr$^{-1}$
  - at Solar Min, only 40 yr$^{-1}$
- **Origin ? : “Magnetic Reconnection Events”**
- **Coronal Mass Ejection**
Solar Activity, Some Facts & Figures (2)

- **Flares**
  - Release of up to $10^{23}$ Joules in 10 – 100 minutes
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    - High particle ($^1$H & e⁻) Flux @ Earth, 1 – 5 days later
  - Frequency
    - at Solar Max, 1500 yr⁻¹
    - at Solar Min, only 40 yr⁻¹
- **Origin ? : “Magnetic Reconnection Events”**
- **Coronal Mass Ejection**
  - Mass expelled $\sim 3 \times 10^{13}$ kg
    - $\sim 2$ km cube of rock (but of course it’s mostly Hydrogen)
  - Energy, also $\sim 10^{23}$ Joules
  - Speed of ejection $\sim 500 – 1500$ km s⁻¹
  - Much of it in the plane of the Ecliptic
Aurora Borealis
Aurora seen from Space