Astronomy Open Night will begin at 7:30 PM
Nuclear Fusion – the Proton-Proton Reaction

Generates about 98% of Solar Luminosity
In a Nuclear Reaction

• Mass is converted to energy \( E=mc^2 \)
  • 0.7% of the mass of 4 protons is lost
  • Sun converts 4 million tons per second to energy

• The number of particles in the core is reduced
  • \( 6 \, p^+ \rightarrow \alpha +2p^+ + 2e^+ \)
    • Neutrinos don’t count
Hydrostatic Balance

• \( P = n k_B T \)  \( n \) is the particle density
• Core pressure \( P_c \) is set by the mass of the Sun
• The number density \( n \) decreases when \( 4p^+ \rightarrow \alpha \)
  - PP: \( 6 p^+ \rightarrow \alpha + 2p^+ + 2e^+ \) net loss of 1 particle
• \( nT \) is \( \sim \)constant, so core temperature \( T \) goes up.
• p-p reaction rate \( \propto T^4 \)
• Luminosity \( L \) scales directly with the nuclear reaction rate.

• So as the Sun shines, it gets brighter with time
• The Sun today generates $4 \times 10^{33}$ ergs of energy every second
• It is all radiated away into space by photons
• One of every 400 thousand trillion of these photons hits the Earth ($2.7 \times 10^{-18}$)
Energy Balance

\[(1-a) \pi R_\oplus^2 \left( L_\odot / 4\pi d^2 \right) \Rightarrow\]

\[\downarrow \]

\[4\pi R_\oplus^2 \sigma T_\odot^4\]
Energy Balance

Earth is in equilibrium

• Output = input
  (if not, the mean temperature would change)

• \(4\pi r_\oplus^2 \sigma T_\oplus^4 = (1-a) \pi r_\oplus^2 \frac{L_\odot}{d^2}\)
  • \(a\): albedo
  • \(d\): Earth-Sun distance
  • \(L_\odot/d^2\) is called the Solar Constant, or the TSI

Solve for \(T_\oplus\).

\[T_\oplus = 247\text{K} \ (-26\text{C}, -15\text{F})\]
Energy Balance

Earth is in equilibrium

- Output = input
  (if not, the mean temperature would change)

- \[ 4\pi r_{\oplus}^2 \sigma T_{\oplus}^4 = (1-a) \pi r_{\oplus}^2 \frac{L_\odot}{d^2} \]
  - a: albedo
  - d: Earth-Sun distance
  - \( L_\odot/d^2 \) is called the Solar Constant

Solve for \( T_{\oplus} \).

\[ T_{\oplus} = 247K \ (-26C, -15F) \]

Why is \( T_{\oplus} = 287K \ (14C) \)?
The Greenhouse Effect

At 247K, the Earth tries to radiate in the IR (Wien’s law)

The atmosphere is not transparent in the IR

:. Heat is trapped
Greenhouse Effect

The blackbody is the most efficient radiator possible. The Earth is not exactly a blackbody. 
It must heat up to compensate.

Greenhouse gases include:
- carbon dioxide (CO₂)
- Methane (CH₄)
- water vapor (H₂O)
- nitrous oxides (NOₓ)
- chlorofluorocarbons,

These all absorb infrared light.
Greenhouse Effect: An Old Concept

- **1827**: Joseph Fourier recognizes the atmosphere is transparent to solar radiation, but largely opaque to thermal radiation.
- **1861**: John Tyndal shows that the greenhouse gases are not O₂ and N₂, but the trace constituents H₂O and CO₂.
- **1896**: S. Arrhenius and T.C. Chamberlain recognize importance of CO₂ feedback.
H$_2$O Opacity

GOES band 6 (2.2 µm)  
GOES band 10 (7.3 µm)
The Faint Young Sun Problem

![Graph showing the freezing point of water and solar luminosity relative to present value over billions of years before present.](image-url)
Earth in Equilibrium

• There was liquid $\text{H}_2\text{O}$ on Earth 4.4 Gya ($\text{Gya} = \text{billion years ago}$)

• There has been permanent liquid water on Earth for at least 3.8 Gyr

• $\therefore$ the surface temperature has been between 273 and 373 K.

• Fossils suggest a much narrower range in $T_{\oplus}$
  • For metazoa: $273 < T_{\oplus}(\text{K}) < 313$
The Primordial Atmosphere

- Concentration of important gases in the atmosphere as a function of time.
- Time (Billions of Years Ago):
  - 4.5
  - 4.0
  - 3
  - 2
  - 1
- Gases:
  - Methane, Ammonia
  - Nitrogen
  - Water
  - Carbon Dioxide
  - Oxygen

Concentration of gases in the atmosphere:
- At 4.5 billion years ago, the atmosphere was unknown.
- As time progressed, the concentration of Oxygen increased significantly.

Diagram illustrates the evolution of the atmosphere over time.
500 Million Years of Global Temperatures

Temperature of Planet Earth

550 million years
Note changes in scale

Over 4 Billion Years

- The greenhouse has diminished
- The Sun has brightened
- Temperatures have trended down
So what of global warming?
500 Million Years of Global Temperatures

550 million years
Note changes in scale

550 Myr of Terrestrial Environment

https://skepticalscience.com
2019 Years of Global Temperatures

Global temperature change over the last 2019 years

Temperature change in °C

- Rabaul eruption
- Medieval Warm Period
- Little Ice Age
- Kuwae eruption
- Tambora eruption
- Modern warming discovered
- Greenhouse effect discovered

Time periods:
- 100 to 900: Lower temperatures
- 900 to 1100: Medieval Warm Period
- 1100 to 1300: Little Ice Age
- 1300 to 1900: Increase in temperature

Data sources:
- PAGES2k
- HadCRUT4.6 for 2001-2019

@ed_hawkins

Modern warming discovered
Greenhouse effect discovered
Temperatures through 2019

Note: this excludes the internal oceanic heating
Total increase in heat content 10 zettaJoules/year;
Equivalent to 5 Hiroshima bombs/second

Source: https://www.climate.gov/
The Sun is complicit on Billion Year timescales

But since 1850?

https://skepticalscience.com
Total Solar Irradiance

TSI = \frac{L_\odot}{d^2}

- The solar forcing is about 1 part in 5500
- That can account for about ± 0.1 °C

Do Terrestrial temperatures track Solar luminosity?
If The Sun is Not to Blame, What Is?
Atmospheric CO₂ at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Global Monitoring Laboratory

Monthly Averages (PPM)
Aug 2019  409.95
Aug 2020  412.55
Natural Variations on an Unnatural Trend

RECENT MONTHLY MEAN CO$_2$ AT MAUNA LOA

![Graph showing recent monthly mean CO$_2$ at Mauna Loa with years from 2016 to 2021.](image)
The Methane Record

Monthly CH$_4$ abundance

May 2020: 1874.7 ppb
May 2019: 1861.9 ppb
This graph shows the correlation between rising levels of carbon dioxide (CO$_2$) in the atmosphere at Mauna Loa with rising CO$_2$ levels in the nearby ocean at Station Aloha. As more CO$_2$ accumulates in the ocean, the pH of the ocean decreases. (modified after R. A. Feely, Bulletin of the American Meteorological Society, July 2008).
Why is CO$_2$ Increasing So Fast?

- Is it geological (volcanoes)?
- Is it anthropogenic?
- And how can we tell?
Burning Carbon Decreases Atmospheric $\text{O}_2$

https://www.skepticalscience.com/anthrocarbon-brief.html
Anthropogenic CO$_2$ Estimate

(dashed): from fossil fuel + cement production
(solid): in atmosphere above pre-industrial baseline
Evidence of Anthropogenic CO₂:

Predictions based on known fossil fuel consumption

https://www.skepticalscience.com/anthrocarbon-brief.html
Burning organic carbon reduces $^{13}\text{C}/^{12}\text{C}$ ratio

https://www.skepticalscience.com/anthrocarbon-brief.html
Looking Ahead
Practical Solar Evolution

The Sun Is Getting Brighter

In about 1 billion years:
• The surface temperature of Earth will exceed 100 °C
• Well before that, temperatures will rise
  • Water will evaporate
  • Earth will become a cloud-covered steam bath
  • Earth will become uninhabitable (for macroscopic life).

In 5-6 billion years:
• The Sun will expand into a red giant
  • The solar radius may reach 1 au
  • Mercury and Venus will be engulfed
  • The Earth’s orbit will expand to about where Mars is today
Conclusions. I

• The Sun, and the Earth, have changed over time
• Equilibrium has been maintained
  • Solar and atmospheric evolution
  • Negative feedbacks – the Carbon cycle
  • Biological feedbacks (Gaia)
• Timescales for changes are 100s of thousands of years or longer
• The Sun will eventually make the Earth uninhabitable
Conclusions. II

• Today we are changing the atmosphere on timescales of decades
• We have the capacity to render the Earth uninhabitable for ourselves

• To paraphrase Wm. Shakespeare:
The fault is not in our star, but in ourselves.
Spares
SED Variability

SOLAR SPECTRUM, VARIABILITY and ATMOSPHERIC ABSORPTION

\[ \text{TOTAL Irradiance} = \int \text{SPECTRAL Irradiance} \approx 1366 \text{ Wm}^{-2} \]

- \( N_2 \)
- \( O_2 \)
- \( O \)
- \( O_2 O_3 \)
- \( H_2O \) & \( CO_2 \)

\[ \text{spectral variability} \]

\[ \text{total variability} \]

\[ \text{spectral irradiance} \]

J. Lean NASA/NRL
Foraminifera Temperature Record

68 Million Years.
Note changes in scale

Source: LiveScience, 9/10/20
10,000 Years of Temperatures

Greenland GISP2 Ice Core - Temperature Last 10,000 Years


Minoan Warming
Roman Warming
Medieval Warming
Global temperature change over the last 2019 years

- Medieval Warm Period
- Little Ice Age
- Rabaul eruption
- Kuwae eruption
- Tambora eruption
- Maunder Minimum
- Tianchi eruption
- Samalas eruption
- Invention of steam engine
- Modern warming discovered
- Greenhouse effect discovered

@ed_hawkins
Data: PAGES2k (& HadCRUT4.6 for 2001-2019)
# Effects of CO$_2$

<table>
<thead>
<tr>
<th>Ppm CO$_2$</th>
<th>Duration</th>
<th>Comment/effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;420</td>
<td>---</td>
<td>Current level</td>
</tr>
<tr>
<td>600</td>
<td>hours</td>
<td>Crowded indoor spaces; Reduced mental performance documented</td>
</tr>
<tr>
<td>1000</td>
<td>hours</td>
<td>Acceptable by ASHRAE guidelines; Reduced test scores documented</td>
</tr>
<tr>
<td>1,200</td>
<td>hours</td>
<td>Typical poorly-ventilated room</td>
</tr>
<tr>
<td>2,500</td>
<td>hours</td>
<td>Significantly reduced mental performance</td>
</tr>
<tr>
<td>3,000</td>
<td>&gt;6 hours</td>
<td>Poor indoor air quality may be noticeable</td>
</tr>
<tr>
<td>5,000</td>
<td>hours</td>
<td>NASA limit for long term spaceflight</td>
</tr>
<tr>
<td>10,000</td>
<td>minutes</td>
<td>Drowsiness</td>
</tr>
<tr>
<td>12,000</td>
<td></td>
<td>Headaches reported</td>
</tr>
<tr>
<td>20,000</td>
<td>Minutes</td>
<td>Poor indoor air quality noticeable</td>
</tr>
<tr>
<td>&gt;20,000</td>
<td>Minutes-hours</td>
<td>Difficulty breathing; possible acidosis</td>
</tr>
<tr>
<td>30,000</td>
<td>Minutes</td>
<td>Breathing rate doubled</td>
</tr>
<tr>
<td>50,000</td>
<td>Minutes</td>
<td>4x normal breathing rate; toxic threshold.</td>
</tr>
<tr>
<td>&gt;50,000</td>
<td>Minutes</td>
<td>Unconsciousness; death</td>
</tr>
</tbody>
</table>

Source: https://inspectapedia.com/hazmat/Carbon_Dioxide_Hazards.php
Earth’s past

**RCP4.5**: 2°C temperature rise by 2100; Requires negative CO$_2$ emissions  
**RCP8.5**: 4°C temperature rise by 2100; Possible is no reduction in CO$_2$ emissions

Will the Sun Come to the Rescue?

The Sunspot - TSI correlation

If the TSI varies by 0.001 (1000 ppm), $T_\oplus$ changes by 0.7°C
(for albedo=0; about +/- 0.2°C in reality)
Little Ice Age

"Sports on a Frozen River" by Aert van der Neer
Maunder Minimum

![Graph showing variations in sunspot groups, Wolf Sunspot Number, and aurorae over the years A.D. from 1600 to 1800.]
Other Grand Minima
Predicting the Future

Abdussamatov, I. 2011, Applied Physics Research, 4, 178
The Little Ice Age

- \( \sim 1350 \) – 1850
- Follows Medieval Warm Period
- Overlaps 3 solar activity minima
  - Sporer
  - Maunder
  - Dalton
Nuclear Fusion – the CNO Cycle
Hydrostatic Balance

• $P = nk_B T$  \( n \) is the particle density

• Core pressure $P_c$ is set by the mass of the Sun

• The number density $n$ decreases when $4p^+ \rightarrow \alpha$
  • PP: $6p^+ \rightarrow \alpha + 2p^+ + 2e^+$ net loss of 1 particle
  • CNO: $^{12}\text{C} + 4p^+ \rightarrow \alpha + ^{12}\text{C} + 2e^+$ net loss of 1 particle

• $nT$ is $\sim$constant, so core temperature $T$ goes up.

• Nuclear reaction rate $\propto T^\beta$, where $\beta \sim 16$ (CNO cycle)

• Luminosity $L$ scales directly with the nuclear reaction rate.