The Sun

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May 7, 2016
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"At first sight it would seem that the deep interior of the Sun and stars in less accessible to scientific investigation than any other region of the Universe. Our telescopes may probe farther and farther into the depths of the space, but how can we ever obtain certain knowledge of that which is hidden behind substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?"

- Sir Arthur Stanley Eddington (1926)
Motivation

Why do we study the Sun?

- The Sun as a Star
- Space Weather
- The Sun as a Physical Laboratory

Sun’s Interior

Sun’s interior furnishes an ideal cosmic laboratory for

- Atomic, Nuclear and Neutrino physics
- High temperature plasma physics and Magnetohydrodynamics
- General Relativity
Resume of the Sun

- Mass = \( (1.9889 \pm 0.0002) \times 10^{33} \text{ gm} \)
- Radius = \( (6.9599 \pm 0.0007) \times 10^{10} \text{ cm} \)
- Luminosity = \( (3.846 \pm 0.006) \times 10^{33} \text{ ergs} \)
- Age = \( (4.6 \pm 0.1) \times 10^9 \text{ yrs} \)
- Chemical composition \( Z/X = 0.0246 \pm 0.002 \)

\( X \) and \( Z \) are respectively fractional abundances by mass of hydrogen and elements heavier than helium.
Structure of the Sun
The Solar Interior

Solar interior is separated into 4 regions by the different processes that occur there.
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The Core

- Central temperature 15,00,000°C
- Central density 150 gm/cm³
The Sun
The Big Questions

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Radiative zone

- Based on method of energy transport
- Major part of the solar interior
The Solar Interior

Solar interior is separated into 4 regions by the different processes that occur there

**The Core**
- Central temperature 15,00,000° C
- Central density 150gm/cm³

**The Interface layer**
- Believed to be the seat for generation of magnetic field
- Highly sheared layer

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The Solar Interior

Solar interior is separated into 4 regions by the different processes that occur there.

**The Core**
- Central temperature $15,000,000^\circ C$
- Central density $150 \text{ gm/cm}^3$

**Radiative zone**
- Based on method of energy transport
- Major part of the solar interior

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**Convection zone**
- Energy transport by convection
- Convective motion visible as granules and supergranules
The Photosphere

- Visible surface of the Sun - 500 km thick
- Sunspots
- Faculae
- Granules
- Measurement of flow of material using doppler effect
- Reveals supergranules, large scale flows and waves and oscillations
The Chromosphere

- Irregular layer above photosphere
- Temperature rises from 6000° C to 20,000° C
- Observed in H-α and Ca-II emission
- Spicules and small-scale magnetic activity
The Sun

The Big Questions

The Transition region

- Separates chromosphere from corona
- Temperature rises from 20,000° C to 1,000,000° C
- Observed in C IV, O IV and Si IV emission
- How the temperature rises is still not properly understood
The Sun
The Big Questions

The Corona

- Sun’s outer atmosphere
- Visible during total eclipse
- Temperature greater than 1,000,000° C
- Observed in X-ray, and emission from heavier elements like Ca, Fe
- Very dynamic - site of solar flares, CMEs
Standard Solar Model

- Spherically symmetric Sun
- Mechanical and thermal balance
- Standard Nuclear and neutrino physics
- Uniform initial chemical composition
- No significant mass loss nor any accretion
- Gravitational settling of Helium and heavy elements beneath the convection zone
- Gravitational pull is balanced by the pressure of expanding matter
- Ideal gas equation holds for solar plasma
Internal structure of the Sun is governed by
  - Mechanical equilibrium
  - Thermal equilibrium

Auxillary input physics

Microphysics:
  - Nuclear energy generation in the core
  - Equation of state of matter

Macrophysics:
  - Turbulent convection
  - Diffusion of helium and heavy elements
Structural equations for spherical Sun

\[ \frac{dM(r)}{dr} = 4\pi r^2 \rho(r) \]

\[ \frac{dP(r)}{dr} = -\frac{GM(r)}{r^2} \rho(r) \]

\[ \rho T \frac{dS(r)}{dr} = -\frac{1}{r^2} \frac{d}{dr} \left( r^2 (F_{\text{rad}} + F_{\text{conv}}) \right) + \rho \epsilon \]

\[ F_{\text{rad}} = -K_{\text{rad}} \frac{dT}{dr}, \quad (K_{\text{rad}} = \frac{4acT^3}{3\kappa \rho}) \]

\[ F_{\text{conv}} = -\kappa_{\text{turb}} \rho T \frac{dS(r)}{dr}, \quad \kappa = wl \]
Solar Model data

Density (Dalsgaard Model 1)

Core

Radiative Zone

Convective Zone

Density (gm/cm³)

0.0 0.2 0.4 0.6 0.8 1.0

Radius

10^{-6}

10^{-4}

10^{-2}

10^0

10^2

Gold

Water

Air

NASA/MSFC Hathaway
Solar Model data - I

Temperature (Dalsgaard Model 1)

Core
Radiative Zone
Convective Zone

Temperature (K)

Radius
Solar Model data - II

Temperature Gradient (Dalsgaard Model 1)

- Adiabatic Gradient
Nuclear energy generation - pp cycle

pp cycle

\[ p + p \rightarrow d + e^+ + \nu_e \quad (\leq 0.42 \text{ MeV}) \]

\[ p + e^- + p \rightarrow d + \nu_e \quad (1.44 \text{ MeV}) \]

\[ p + d \rightarrow ^3\text{He} + \gamma \]

pp-I: \[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p \]

\[ ^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e \quad (\leq 18.8 \text{ MeV}) \]

pp-II: \[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \]

\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e \quad (0.38, 0.86 \text{ MeV}) \]

\[ ^7\text{Li} + p \rightarrow ^8\text{Be} + \gamma \]

\[ ^8\text{Be} \rightarrow 2^4\text{He} \]

pp-III: \[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \]

\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \]

\[ ^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu_e \quad (\leq 14.6 \text{ MeV}) \]

\[ ^8\text{Be} \rightarrow 2^4\text{He} \]
Nuclear energy generation - CNO cycle

CNO cycle

\[
\begin{align*}
^{12}\text{C} + p & \rightarrow ^{13}\text{N} + \gamma \\
^{13}\text{N} & \rightarrow ^{13}\text{C} + e^+ + \nu_e \quad (\leq 1.2 \text{ MeV}) \\
^{13}\text{C} + p & \rightarrow ^{14}\text{N} + \gamma \\
^{14}\text{N} + p & \rightarrow ^{15}\text{O} + \gamma \\
^{15}\text{O} & \rightarrow ^{15}\text{N} + e^+ + \nu_e \quad (\leq 1.7 \text{ MeV}) \\
^{15}\text{N} + p & \rightarrow ^{12}\text{C} + ^4\text{He} \\
\text{OR} \\
^{15}\text{N} + p & \rightarrow ^{16}\text{O} + \gamma \\
^{16}\text{O} + p & \rightarrow ^{17}\text{F} + \gamma \\
^{17}\text{F} & \rightarrow ^{17}\text{O} + e^+ + \nu_e \quad (\leq 1.7 \text{ MeV}) \\
^{17}\text{O} + p & \rightarrow ^{14}\text{N} + ^4\text{He}
\end{align*}
\]
Solar Neutrino Experiments

Goals:

- To test physics of nuclear reactions operating in the solar core
- To confirm nature of thermonuclear energy generation in the Sun, proton-proton chain, C-N-O cycle
- To study the properties of Neutrinos

Motivation for the chlorine experiment setup by Davis (1965)
”To see inside the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars”
Solar Neutrino Puzzle

Unreactive and Large mean free path !!!

Solar neutrinos originate from the core of the Sun due to thermonuclear reactions and thus offer the possibility of probing solar interior. They are highly unreactive and even pass through the Earth undetected. Flux at Earth is of the order $10^{11}/cm^2s$.

The Puzzle

Computational models predict an estimate of number of neutrinos that can be detected from Sun. But the experimental results show a large discrepancy.
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So the puzzle, NEUTRINOS ARE MISSING !!!!
Experimental Techniques

Radiochemical experiments

\[ ^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^- (\geq 0.814\text{MeV}) \]

\[ ^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^- (\geq 0.233\text{MeV}) \]

Super Kamiokande

Elastic scattering of Neutrinos by electrons

\[ e^- + \nu_x \rightarrow e^- + \nu'_x (\geq 5\text{MeV}) \]
Sudbury Neutrino Observatory

Heavy water cerenkov

\[ d + \nu_e \rightarrow p + p + e^- (\geq 5 \text{MeV}) \]

\[ d + \nu_x \rightarrow p + n + \nu'_x (\geq 5 \text{MeV}) \]

\[ e^- + \nu_x \rightarrow e^- + \nu'_x (\geq 5 \text{MeV}) \]
R = Measured Neutrino Flux/Predicted model Neutrino flux

SK and SNO results together confirmed that the NEUTRINOS ARE NOT MISSING !!! They suffer from Multiple Personality Disorder.
Is Sun a boring star???
Multiwavelength Sun
Sun is a magnetically active star!!!
Coronal loops
Magnetic Reconnection
Magnetic fields in the Sun

One of the longest recorded observational data in Physics

Solar activity rises and falls with an ‘\( \sim 11 \) year cycle’

Signatures
Butterfly diagram
Hale’s Polarity law
Joy’s law

Image Credits: HAO website
Magnetic fields in Sun are observed to follow a temporal (∼11-year) and spatial coherency resulting in a butterfly diagram.

Torsional Oscillations in Sun also follow a similar coherency.
How are magnetic fields generated, sustained and re-generated in the Sun?
The Sun

The Big Questions

Solar Dynamo Theory

The Dynamo Process

Used to explain the generation of magnetic fields in Sun against Ohmic dissipation

$\alpha$ and $\Omega$ effect

Dynamo: convection zone or tachocline??? - Helioseismology

Magnetic buoyancy and $\alpha$ effect
Flux Transport Dynamo Models (FTDMs)

- Kinematic solar dynamo model - $v$ known
- Meridional Circulation, differential rotation, magnetic buoyancy, Babcock-Leighton process, turbulent diffusivity important players in determining magnetic field generation
The Big Questions

How do we study the interior of the Sun???

Helioseismology

- Analogous to seismology, where the Earth’s interior is studied by monitoring waves caused by earthquakes
- Convection is source of waves in Sun
- On Sun’s surface, the waves appear as up and down oscillations of the gases, observed as Doppler shifts of spectrum lines.
Results from Helioseismology
Results from Helioseismology

Differential Rotation
Latitudinal dependence
Results from Helioseismology

**Differential Rotation**
- Latitudinal dependence

**Tachocline**
- Highly sheared layer
Results from Helioseismology

Differential Rotation
Latitudinal dependence

Tachocline
Highly sheared layer

Sound speed and density
Using equations of mechanical equilibrium
Results from Helioseismology

Differential Rotation
Latitudinal dependence

Tachocline
Highly sheared layer

Sound speed and density
Using equations of mechanical equilibrium

Temperature and Chemical composition
Equations of thermal equilibrium and energy transport
The Sun

The Big Questions

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The Coronal Heating Process

The Sun's corona is hotter than 1,000,000°C while the visible surface is at about 6,000,000°C. The nature of the processes that heat the corona is a mystery.

The Nature of Solar flares

Time scales at which Solar flares occur and the exact physics behind it is unknown.

The Origin of the Sunspot cycle

The origin of 11 year solar cycle, intricately related to the magnetic activity is unknown. How the dynamo actually works in the Sun is uncertain.
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References

- Image credits: www.nasa.gov.in
- NASA SDO website
- Presentations from Prof. S.M. Chitre and Dr. Aniket Sule
Thank You ...