The Sun and the Stars

1992 June 07
Stellar Lifecycle
Starbirth

Orion Nebula Mosaic
HST · WFPC2
PRC95-45a · ST ScI OPO · November 20, 1995
C. R. O’Dell and S. K. Wong (Rice University), NASA

Protoplanetary Disks
Orion Nebula
HST · WFPC2
PRC95-45b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O’Dell (Rice University), NASA
Young Stars

Gaseous Pillars • M16
HST • WFPC2
PRC95-44a • ST ScI OPO • November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

Dr Matt Burleigh
Globular Clusters

Globular Cluster M15
PRC95-06 • ST ScI OPO • November 1995 • P. Guhathakurta (UC Santa Cruz), NASA

HST • WFPC2
Star Death
Star Death
Aims and Objectives

To introduce you to the properties of the Sun and the stars, and their evolution

This will be fairly descriptive: in the second and third year you will learn the detailed physics underlying our understanding.
Lifecycles of Stars

- **Unit 1 – The Sun**
  - Structure, limb darkening, magnetic field & solar cycle

- **Unit 2 – Stars**
  - Classification from spectra, measuring distances, masses and radii, the Hertzsprung-Russell diagram

- **Unit 3 – Stellar evolution**
  - The life cycles of stars of different masses

- **Unit 4 – Stellar Structure**
  - Energy generation, hydrostatic equilibrium

- **Unit 5 – Stars of special interest**
  - Binary stars, pulsating stars, stellar remnants
Reference material

- Astronomy and Astrophysics (Zeilik and Gregory), 4th edition
Sun:
centre of our solar system. Our nearest star (closer by a factor of $2 \times 10^5$), therefore the best understood.

Vital statistics:

Distance $150 \times 10^6$ km = 1 AU (astronomical unit) = 8 light-minutes

Radius $6.95 \times 10^5$ km = $1 R_\odot$

Apparent diameter $\frac{1}{2}$ degree

Mass $1.99 \times 10^{30}$ kg = $1 M_\odot$

Luminosity $3.8 \times 10^{26}$ W (J/s) = $3.8 \times 10^{33}$ erg/s = $1 L_\odot$

Effective temperature $T_{\text{eff}} = 5770$ K

Composition (by mass) 74% Hydrogen, 24% Helium, 2% other elements (metals)

Age $\sim 4.5 \times 10^9$ years
Energy generation (solar):

Not chemical, gravitational ($10^7$ years) $\times$

**Nuclear Fusion**: proton-proton chain

slow – involves weak interaction

5x10$^9$ yrs $^1$H + $^1$H $\rightarrow ^2$H + e$^+$ + $\nu_e$ +0.42 MeV

e$^-$ + e$^+$ $\rightarrow 2\gamma + 1.02$MeV

1 s $^2$H + $^1$H $\rightarrow ^3$He $+ \gamma + 5.49$MeV

3x10$^5$ yrs $^3$He +$^3$He $\rightarrow ^4$He + $^1$H $+$12.86MeV (PPI)

Net result

$^4$H $\rightarrow ^4$He + 2e$^+$ +2$\nu_e$ + 2$\gamma$

$M_{He} = 4 ~ M_H \times 0.993 ~ (0.7\% \text{ lost})$

$2e^+ + 2e^- \rightarrow 4\gamma$

$E = \Delta m \ c^2$

$2\nu_e$ fly out with no interaction (very, very small x-section for interaction)

6 $\gamma$ undergo multiple scatterings, reach photosphere after $\approx 10^5$ years
proton-proton chain

\[
\begin{align*}
1^1H + 1^1H & \rightarrow 2^2H + e^+ + \nu_e \\
2^2H + 1^1H & \rightarrow 3^3He + \gamma \quad \text{(cycle ends here for low-mass stars!)}
\end{align*}
\]

\[
\begin{align*}
3^3He + 3^3He & \rightarrow 4^4He + 2^1H \\
3^3He + 4^4He & \rightarrow 7^7Be + \gamma \quad \text{(10^6 yrs)}
\end{align*}
\]

\[
\begin{align*}
\text{(PPI, } T\sim 1.0-1.4\times 10^7 \text{ K)}
\end{align*}
\]

\[
\begin{align*}
7^7Be + e^- & \rightarrow 7^7Li + \nu_e \\
7^7Be + 1^1H & \rightarrow 8^8B + \gamma \quad \text{(66 years)}
\end{align*}
\]

\[
\begin{align*}
\text{(PPII, } T\sim 1.4-2.3\times 10^7 \text{ K)}
\end{align*}
\]

\[
\begin{align*}
8^8B & \rightarrow 8^8Be + e^+ + \nu_e \quad \text{(0.9secs)}
\end{align*}
\]

\[
\begin{align*}
8^8Be & \rightarrow 2^4He \quad \text{(9.7\times 10^{-17} secs)}
\end{align*}
\]

\[
\begin{align*}
\text{(PPIII, } T>2.3\times 10^7 \text{ K)}
\end{align*}
\]
**Structure**

- **Photosphere** (T~5800K)
- **Convection zone** (T~2x10^6 K)
- **Radiative zone** (T~10^7 K)
- **Corona** (T~2x10^6 K)
- **Chromosphere**
- **Thermonuclear Core** (T~1.5x10^7 K)
**Core**: 
Sight of thermonuclear reactions, extends out to 0.25R☉ 
T~1.5x10^7 K, ρ~150 g/cm^3 (≈10x ρ\textsubscript{gold}). 
Nuclear burning almost completely shut off beyond 0.25R☉

**Radiative zone**: 
Extends from 0.25-0.7R☉ (the tachocline or interface layer). 
Energy transported by radiation. 
Photons scatter many times, take approx 10^5 years to reach interface layer. 
Density falls from 20 g/cm^3 to 0.2 g/cm^3, 
T falls from 7x10^6 K to 2x10^6 K over same distance.

**Tachocline** (interface layer) : 
Lies between radiative zone and convection zone. 
Thought to be site of magnetic field generation. 
Shearing (ie. changes in fluid velocities) in this layer can stretch and enhance magnetic field lines.
**Convection zone:**

0.7R☉ – to photosphere (visible surface).

At base, T ~ 2x10^6 K, cool enough for heavier elements (e.g. C, N, O, Ca, Fe) to hang onto some of their electrons.

Increased opacity, makes it harder for photons to get through.

Trapped heat makes the fluid unstable and it starts to convect (boil).

Convection carries heat rapidly to surface.

Material expands and cools as it rises.

Temperature at surface (photosphere) ~ 5770 K, \( \rho \sim 2 \times 10^{-7} \) g/cm³.
**Photosphere**: The visible surface of the sun. Layer ~ 100 km thick at top of convection zone. Surface has non-uniform intensity (limb darkened). Photosphere exhibits a number of surface features, dark sunspots, bright faculae, and granules.

- **sunspot**

- **umbra**

- **Penumbra**
  - Strongly magnetic regions 2000K cooler than rest of surface.

- **Faculae**
  - Bright areas of concentrated magnetic field

- **granules**
  - each granule is ~ 1000 km across
  - Granules are transient
  - Granules are tops of convection cells
**Chromosphere:**
Irregular layer above photosphere, T~20,000 K. At this temperature, gas emits strongly in H\(\alpha\) (6563 Å, 1Å=10^{-10} m). When observed through H\(\alpha\) filter, sun displays new features, the chromospheric network, filaments, plages, prominences and spicules.

**H\(\alpha\) observations of the sun**

- **Plages** – bright patches in H\(\alpha\) light surrounding sunspots
- **Filaments** – Dark areas in H\(\alpha\) light. Cool, dense clouds suspended above surface by magnetic field.
- **Prominences** – Filaments seen at Sun’s limb
- **Spicules** – small, jet like eruptions seen as dark streaks in H\(\alpha\) light. Last a few minutes.
Transition region:
Separates hot corona from chromosphere. Heat flows from corona into chromosphere, producing thin layer where temperature changes very rapidly (T~10^6K – 20,000K). Hydrogen is completely ionised, emission dominated by highly ionised lines of C, O and Si (CIV, OIV, SiIV). These are ultraviolet lines and can only be seen from space by satellite observatories.

SOHO (Solar Heliospheric Observatory) observation of the transition region CIV emission.
**Corona:**

Suns outer atmosphere, visible only during total eclipse or with use of a coronographic disc (an opaque disc which blocks the light from the photosphere). $T > 1 \times 10^6$ K. Elements H, He, C,N,O completely stripped. Emission dominated by heavy trace elements e.g. Ca and Fe. The corona displays a number of features including; streamers, plumes, coronal loops and holes.

Coronal gas hot enough to emit low energy X-rays
X-ray images show irregular gas distribution
Large loop structures $\Rightarrow$ hot gas trapped in magnetic loops
Dark regions (gas less hot and dense) $\Rightarrow$ coronal holes
Holes correspond to magnetic field lines that do not reconnect with the surface

**Plume –**
streamers at poles associated with open field lines

**coronal loop –**
associated with closed field lines between sunspots

**coronal hole –**
associated with open field lines. Seen in Xrays.
**Solar wind:**

Solar gravity is insufficient to retain high temperature coronal gas
Gas is a plasma (ionized but electrically neutral on a large scale)

Material from outer corona blows off into space, usually along open field-lines (e.g. coronal holes), but also following solar flares.

Mass loss \( \sim 10^{-13} \, M_{\text{sun}}/\text{yr} \)

Wind accelerates as it expands: 300km/s at 30\( R_{\text{sun}} \) \( \Rightarrow \) 400km/s at 1 AU
Proton/electron energy \( \sim 10^3 \text{eV} \)
Density at Earth \( \sim (0.4-8.0) \times 10^6 \text{m}^{-3} \)
Putting it all together