“Willingly would I burn to death like Phaeton, were this the price for reaching the Sun and learning its shape, its size and its substance.”

-Eudoxus
The Sun in Visible Light

1992 June 07
H alpha (656.3 nm ~ 10000K)
NASA GSFC
Ca II 854.2 nm longitudinal magnetograms from the U.S. National Solar Observatory SOLIS vector spectromagnetograph (VSM) at Kitt Peak (Arizona) [2007/02/05 19:17 UT]
Photospheric longitudinal magnetograms from the U.S. National Solar Observatory SOLIS vector spectromagnetograph (VSM) at Kitt Peak (Arizona) [2007/02/05 20:52 UT]
On a More Violent Day
Ultraviolet
Sizes
Jupiter is about 1 pixel in size
Earth is invisible at this scale
Details
The Core

Core is hot: 15,000,000° C and dense: 150 gm/cm³ (10 times the density of lead) 50% of the Sun’s mass is in the core.

The core is where the nuclear reactions take place. Our Sun fuses Hydrogen into Helium releasing heat energy.

The heat energy generated here keeps the Sun from collapsing gravitationally.

http://www.solarobserving.com/pics/solar-anatomy.jpg
The Radiative Zone extends from 25% to 70% of the Sun’s radius.

Heat is transported here by gamma rays that scatter repeatedly through the dense gas.

The temperature decreases from 7,000,000° C to 4,000,000° C.
The Convection Zone delivers heat to the surface via convection cells.

The convection zone and everything below it is so dense that the gas is opaque to photons. That is light cannot travel far without being absorbed and re-emitted over and over again.

The temperature is only $1,000,000^\circ C$. 

http://www.solarobserving.com/pics/solar-anatomy.jpg
Convection Cells

Above: The sun in white light (420 nm).
Above-right and right: From SOT showing in detail solar granulation (convection cells), and bright points between granules that are locations of concentrations of magnetic field.
The Photosphere

The Photosphere is the region where the Sun’s atmosphere become transparent to photons.

The photons take 100,000 years to travel from the core to the surface.

After wandering for 100,000 years, the photons race out of the photosphere at the speed of light. They reach Earth (93 million miles away) only 8.5 minutes later!

The temperature here is 6000° C

http://www.solarobserving.com/pics/solar-anatomy.jpg
The Chromosphere is about 2000-3000 km thick. The temperature increases here from 6000° C to about 20000° C.

The Hydrogen here is ionized and recombination occurs, this results in the Hα spectral line, which is reddish.

This is where the reddish Prominences occur.

http://www.solarobserving.com/pics/solar-anatomy.jpg
The Corona (Latin for Crown) is the outer atmosphere of the Sun and is best seen during an eclipse.

The Corona is extremely hot at 2,000,000° C. It is much hotter than the photosphere, which was a mystery since the heat comes from the inside!

We have recently learned that energy in the magnetic field heats the corona to its high temperatures.

http://www.solarobserving.com/pics/solar-anatomy.jpg
The Corona
Corona
Sunspots
Galileo’s Observations of Sunspots
Sunspots in Visible Light

Sunspots are cooler than the rest of the surface of the Sun.
Sunspots are Related to Magnetic Fields

Photospheric longitudinal magnetograms from the U.S. National Solar Observatory SOLIS vector spectromagnetograph (VSM) at Kitt Peak (Arizona) [ 2007/02/05 20:52 UT ]
Sunspot Close Up
Side View of a Sun Spot
Magnetic Field around a Sun Spot
The Plasma of the Sun Creates Magnetic Fields and Reacts to the Same Magnetic Fields
Surface of the Sun seen by HiNode
11 Year Solar Cycle
The Solar Cycle in X-Ray
The Magnetic Field Twists and Tangles
Magnetic Field of the Sun
Coronal Loops

The plasma follows the loops of the magnetic field lines.
Prominence

The footprints of the Coronal Loop are the Sunspots.
Super Prominence
Twin Prominences
Solar Flares

Solar flares occur when magnetic energy that has built up in the twisted magnetic fields is suddenly released.

The amount of energy is on the order of billions of kilotons of TNT... the atomic bomb dropped on Hiroshima was 20 kTons.

Flares can result in matter blasting off the surface of the Sun. This is called a Coronal Mass Ejection.
Evolution of the Magnetic Field

1. Coronal Mass Ejection
2. Hot Spot Generates Flash of Light

http://cse.ssl.berkeley.edu/SEGwayed/lessons/exploring_magnetism/in_Solar_Flares/s4.html#sf
Enormous Coronal Mass Ejection
Enormous Coronal Mass Ejection
Coronal Mass Ejection
Flare sets off Solar Tsunami
Coronal Mass Ejection

Approx. size of Earth
Coronal Mass Ejections and the Aurora
Particle Blast Movie
Solar Wind and Space Weather

The Solar Wind is the constant stream of high energy particles being blown off the surface of the Sun. These particles can come in steady flows or huge bursts when there is a CME. This wind is the main source of Space Weather.

Space Weather Now
http://www.sec.noaa.gov/SWN/
Stars
Sirius and Orion
The Sirius System

The Sirius System is 8.6 LY from Earth. Sirius A and B orbit one another with a period of 50.9 years. Sirius B is slightly smaller than Earth. The gravity on its surface is 350,000 times that of Earth’s. A 150 lb person would weigh 50 million pounds on Sirius B!
Sirius A and B orbit one another with a period of 50.9 years
Binary Star Systems

More than half of the stars in the sky are binary star systems!

Stars of equal mass orbit a common center of mass

Stars of unequal mass orbit a common center of mass

Stars of unequal mass orbit a common center of mass

Stars of unequal mass orbit a common center of mass

A highly elliptical orbit. Sirius A and B follow this pattern, except that one star is much more massive than the other

More than half of the stars in the sky are binary star systems!
Alpha Centuri and its partner stars are about 4 Light Years from the Sun
Movie of Proxima Centauri
Triple Star Systems

Two stars orbit closely, and one far away. Note how the center of mass of the pair orbits the center of mass of the triple.

The Centuri system

These three stars orbit one another.
Quadruple Star Systems

Two pairs of stars orbit one another about a common center of mass.

This stable orbital pattern consists of two closely orbiting stars, one star orbits closely with the pair, and the outer star orbits with the triple.
These stars were all born from the same cloud of gas. Remnants of the cloud are still seen as glowing wisps.
Two Open Star Clusters

Astronomy Picture of the Day: 10 Sept 2006
Open Cluster Pismis 24-NGC-6357

The open cluster Pismis 24 is seen above the emission nebula NGC 6537. This complex is some 8000 LY from Earth.

Pismis 24 contains some of the most massive stars on the order of 100 times the mass of the Sun!
Globular clusters are groups of stars that formed from the same cloud and are gravitationally bound to one another. They are typically found in the halo surrounding our galaxy. This cluster has 100,000 stars!

They orbit one another like a swarm of bees.

Sometimes stars are ejected from the cluster, as are presumably planets!
Globular Cluster Omega Centauri
Run-Away Star
Variable Stars in M3 (RR Lyrae Stars)
Orion

Betelgeuse is a Red Supergiant (400 LY away)

Rigel is a Blue Supergiant (800 LY away)

Photo Credit: Matthew Spinelli
Hertzsprung-Russell Diagram

The luminosity (brightness) of a star is related to its temperature (color).

Stars are classed by their temperatures.

Our Sun is a G2 star with a photosphere temperature of about 6000 K. This makes it a yellow star.

http://www2.sunysuffolk.edu/pappasm/AST101/Star_Properties.jpg
Betelgeuse

Size of Star

Size of Earth's Orbit

Size of Jupiter's Orbit

Atmosphere of Betelgeuse · Alpha Orionis

Hubble Space Telescope · Faint Object Camera
Life Cycle of a Star

1. Stellar Nebula
2. Average Star
3. Massive Star
4. Red Supergiant
5. Red Giant
6. Planetary Nebula
7. Supernova
8. White Dwarf
9. Neutron Star
10. Black Hole

http://www.seasky.org/cosmic/assets/images/starlife.jpg
Stars with Mass $< 10$ Solar Masses
Life Cycle of the Sun

http://www-nutev.phyast.pitt.edu/~naples/class/evol/bbtlf1412_a.jpg
Another View of Solar Evolution
Nuclear fusion occurs in the high temperature and density present in the core and generates thermal pressure, which acts against the attractive gravitational forces.

As long as there is sufficient fuel in the core, the star remains in this steady-state.
Stars eventually run out of Hydrogen to fuse, and begin to collapse cramming more matter into the core. The greater densities and pressures allow creation of C N and O. The star swells and cools to become a Red Giant spewing organics into space. When its fuel runs out, the star collapses into a hot White Dwarf.
During the collapse of the Red Giant into a White Dwarf much of the tenuous outer atmosphere of the star is thrown off.

A fast stellar wind from the now hot star forms a bubble inside the shell of gas.
Planetary Nebula

The speed of the expanding shell is Mach 1 – the local speed of sound.

\[ T \sim 10,000 \, \text{K} \]

\[ m \sim m_H \]

\[ v \sim \sqrt{\frac{kT}{m}} \]

\[ v \sim 10 \, \text{km/sec} \]
How are they Illuminated?

Ultra-violet radiation from the hot white dwarf ionizes the gas in the nebula. Recombination occurs and visible light is emitted.

Hence, the ionizing radiation from the star is absorbed by the nebula and re-emitted in the visible range.

NGC 3242
Balick, Hajian, Terzian, Perinotto, Patriarchi
The Cat's Eye Nebula, NGC 6543, imaged by the Hubble Space Telescope. Compare this to the lower magnification ground-based image (inset) made using the 2.1-m telescope at Kitt Peak National Observatory under excellent atmospheric conditions. The Hubble image was obtained by P. Harrington, K.J. Borkowski, and NASA and recolored by B. Balick with permission. The ground-based image is by B. Balick.

The Cat's Eye Nebula was the first planetary nebula ever to be discovered — and also the first to be observed after the refurbishment of the Hubble Telescope's optics.
Watch the Expansion!
Five Years Later
Various Morphologies

Planetary Neb NGC 2610
R G B: [N II] 400s-[O III] 400s He II 400s KPN0 2.1m, Ref: Balick 1987 AJ 94 671

Ring Nebula
Hubble Heritage Team

Planetary Neb NGC 3587 = Owl Nebula
R G B: [N II] 600s-[O III] 600s He II 600s KPN0 2.1m, Ref: Balick 1987 AJ 94 671

NGC 3242
Balick, Hajian,
Terzian, Perinotto, Patriarchi
Various Morphologies

IRAS 17150
Cotton Candy Nebula
Kwok, Su, Hrivnak

Hourglass Nebula - MyCn18
HST - WFPC2

Twinjet Nebula
Balick, Icke, Mollena
White Dwarves

White Dwarves are dense stars. Imagine taking the mass of the Sun and cramming it down to a sphere about the size of the Earth!

It is the Fermi pressure between electrons and protons that keeps the White Dwarf from gravitational collapse.

A teaspoon of white dwarf material would weigh tons!

Sirius A and B. Sirius A is a white A1Vm star, Sirius B is a White Dwarf. The Sirius system is 8.6 Light Years from Earth.
The Sirius System is 8.6 LY from Earth.
Sirius A and B orbit one another with a period of 50.9 years.
Sirius B is slightly smaller than Earth.
The gravity on its surface is 350,000 times that of Earth’s.
A 150 lb person would weigh 50 million pounds on Sirius B!
Sirius A and B

http://www2.sunysuffolk.edu/pappasm/AST101/Star_Properties.jpg
Stars with Mass > 10 Solar Masses
Evolution of a Massive Star
Structure of a Star Before Core Collapse

Elements up to the weight of Iron (Fe) are generated by nuclear fusion in giant stars.

When the core collapses, the star explodes in a supernova.

During a supernova, heavier elements are created: Lead, Silver, Gold, Uranium, etc.

Many of your atoms were created in one or more supernovae!
Supernova 94d

Massive stars explode releasing the energy of 100 billion stars at once!

The bright star in this picture is actually a supernova in another galaxy!

It is putting out more energy than all the other stars together.
Tycho’s Supernova Remnant

Believe it or not, this is the remnant of the Supernova observed by Tycho Brahe on November 11, 1572.

This image is in false color, with Red, Green, and Blue mapped onto particular spectral lines of recorded light.

What you see here is a shell of debris.
Supernova Remnant

This supernova was recorded by the Chinese on July 4, 1054 AD.

It was brighter than Venus, and was visible during the day for 23 days!

It was visible at night for almost 2 years!

It was also recorded by Native Americans in the southwest.

This is what it looks like today.

The Crab Nebula in Taurus (VLT KUEYEN + FORS2)
Largest Supernova Ever Observed!

SN2006gy is the largest supernova ever observed.

It was 100 times more powerful than the previous supernovae, which suggests new unknown mechanisms are at work.

One idea is that the core itself exploded.

The brightness of SN2006gy peaked after 70 days as compared to a few weeks for other supernovae.
Supernova SN2006gy was discovered by a Texas graduate student.

It is in the galaxy NGC 1260 which is 240 million LY away.
Eta Carinae
Eta Carinae

Eta Carinae is a massive star on the order of 100 – 120 times the mass of the Sun!

It is about 7500 Light-Years away
(1 LY is about 6 Trillion Miles)

It experienced a massive eruption in the 1800s, which resulted in the debris that we still see today.

It could go supernova at *any time*. When it does, you’ll be able to read a book by its light!
Stellar Remnants with Mass between 1.4 to 3 Solar Masses
Neutron Stars

When stars are very massive even the electron pressure cannot prevent their collapse.

In this case the electrons combine with the protons, and the star becomes a mass of neutrons.

Neutron stars are about 20 miles across.

Crab Pulsar
Pulsars

Pulsars are neutron stars with intense magnetic fields on the order of

They spin at high rates with periods on the order of milliseconds.
Crab Nebula Pulsar

Supernova remnant from 1054 AD
Gamma-Repeater

credit: Kouveliotou, NASA & USRA
Star Quakes

These gamma ray bursts originate from star quakes.

The spinning neutron star’s crust feels forces from the strong gravitational field of the star, as well as the magnetic field. Overall, the magnetic field works to slow down the rotation of the star.

These competing stresses on an unstable star crust result in cracks and star quakes.

During a quake the star can collapse slightly changing its moment of inertia. Conservation of angular momentum results in the star speeding up its rotation rate.
Anatomy of a Pulsar

- **Atmosphere**: Superhot plasma
- **Outer crust**
  - Starquakes
  - Crystal lattice: 200 m deep nuclei + electrons
- **Inner crust**
  - Starquakes
  - Crystal lattice: 1 km deep nuclei + electrons + neutron drip
- **Outer core**
  - Atomic particle fluid
- **Inner core**
  - Solid block of subatomic particles?

http://science.nasa.gov/newhome/headlines/mag_pix/xsection.jpg
Magnetars

Magnetars are Neutron Stars with extremely powerful magnetic fields.

Magnetars have fields on the order of $10^{15}$ Gauss!
SGR 1806-20

SGR 1806-20 is a magnetar with a field of 800 Trillion Gauss. It is 50,000 Light Years away.

Radius: 20 kilometers
Period: 7.5 seconds
Surface Velocity: 30,000 km/h

On Dec 27, 2004 the light from an explosion on the surface of SGR 1806-20 reached Earth. In only one-tenth of a second the magnetar released more energy than our sun has in 100,000 years: $1.3 \times 10^{39}$ Joules.

If this magnetar had been 10 LY from Earth, the blast would have obliterated our ozone layer!
Stellar Remnants with Mass > 3 Solar Masses
Black Holes

Black Holes are the collapsed remains of supermassive stars.

The Black Hole itself has collapsed to the point where not even light can escape.
Black Hole at the Center of our Galaxy

The Centre of the Milky Way
(VLT YEPUN + NACO)
Black Hole at the Center of our Galaxy
Sun