Activity 2: Anatomy of the Sun
Summary

In this Activity, we will investigate

(a) the structure of the Sun, and variations in temperature and density at different radii;

(b) a hypothetical journey of a photon as it moves to the Sun’s surface after being produced in the core; and

(c) how we measure the properties of light coming from the Sun, and so use the spectra obtained to learn about the composition of, and activity in, the Sun.
(a) Structure of the Sun

The Sun has less distinct structures than the Earth.

There are no distinct zones in the Sun such as we are used to seeing on Earth and in other celestial bodies.

On Earth, there are pretty distinct borders between the sea and the land.
(a) Structure of the Sun

The Sun has less distinct structures than the Earth.

There are no distinct zones in the Sun such as we are used to seeing on Earth and in other celestial bodies.

The bands and gaps in the rings of Saturn look clear, at least from Earth.
(a) Structure of the Sun

The Sun has less distinct structures than the Earth.

There are no distinct zones in the Sun such as we are used to seeing on Earth and in other celestial bodies.

The “seas” and mountains of the Moon are reasonably well-defined to the human eye and the human imagination.
However the Sun has no distinct edges on its surface. Astronomers find it useful to think of the sun in terms of regions where different processes are occurring.
Structure

Astronomers divide the Sun into layers (like those of an onion) to help them to understand and discuss stars.

As light passes from the core to the surface of the Sun and beyond, it is involved in different interactions and changes. Each “skin” or layer of the onion is a region where a particular interaction or change dominates.
Qualities, not composition

Initially, there was virtually no difference between the composition of these layers in the Sun. They all consisted of mostly hydrogen, with some helium and traces of heavier elements.

72% hydrogen
26% helium
2% heavier elements

... all layers the same
The Six Regions of the Sun

However the gas behaves differently at different depths. It is convenient for astronomers to consider the Sun as made up of six regions:

- the **core**, about 25% of the Sun’s radius, about 10,000,000 K
- the **radiative zone**, out to about 70% of the Sun’s radius, about 8,000,000 K
- the **convection zone**, about 30% of the rest of the Sun’s radius, about 500,000 K
  - the **photosphere**, about 500 km thick, about 6000 K
  - the **chromosphere**, about 10,000 km thick, from 4000 K to 400,000 K
- the **corona**, very large and unstable in shape and depth, about $10^6$ K (1,000,000 K)
More about the regions

Here is a table showing the differences between the various regions of the Sun. The radius of the Sun is about $7 \times 10^8$ m, or 700 000 km. At the core, the density is about 160 times that of water, and the pressure is 250 billion times that of Earth’s atmosphere at sea level.

<table>
<thead>
<tr>
<th>region</th>
<th>thickness</th>
<th>temperature</th>
<th>energy transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>core</td>
<td>150 000 km radius</td>
<td>10-16 million</td>
<td>radiation</td>
</tr>
<tr>
<td>radiative zone</td>
<td>300 000 km</td>
<td>8 million</td>
<td>radiation</td>
</tr>
<tr>
<td>convective zone</td>
<td>200 000 km</td>
<td>below .5 million</td>
<td>convection</td>
</tr>
<tr>
<td>photosphere</td>
<td>only 500 km</td>
<td>4200-6400</td>
<td>radiation</td>
</tr>
<tr>
<td>chromosphere</td>
<td>only 10 000 km</td>
<td>4200 to 1 million</td>
<td>radiation, magnetism</td>
</tr>
</tbody>
</table>
More on the regions

As the experts say, “One picture is worth a thousand words.”

This picture is not to scale, the figures are approximate and the colours are obviously fiction!

The interior of the Sun is approximately 25% core, 45% radiative zone, 30% convective zone.

- Core: radius = 150,000 km
- Radiative zone: 300,000 km thick
- Convective zone: 200,000 km thick
- Photosphere: 500 km thick
- Chromosphere: 10,000 km thick
- Corona: 5,000,000 km thick
The Big Questions

1. Why does the temperature drop so dramatically in the photosphere, and then rise again in the chromosphere to be very high again in the corona?

2. Has it got anything to do with the difference in method of energy transport between the regions of the Sun?

In search of answers to these questions, we shall soon follow the imaginary adventures of a photon on its way to the solar surface.
Energy transport

Before embarking on the journey from the core of the Sun to the corona, we must understand the differences between various types of energy transport:

- Conduction
- Convection
- Radiation

"I already know that stuff."

"I don’t! Tell me more!"
A State of Balance

The Sun remains at a fairly stable size and temperature as long as there is a balance between the various forces that might cause it to change.

Before looking at the details of this, let’s examine a similar situation closer to home: an inflated party balloon.
Balance in a Balloon

In an ordinary balloon, the outward pressure of the gas inside is higher than that outside, so provides a force that if unopposed will expand the balloon.

At the same time the stretching of the balloon material provides a force (tension) that if unopposed will collapse the balloon.

So if air leaks out of the balloon and the pressure goes down, the balloon will shrink. But if the pressure increases and the balloon material can’t match it, the pressure will win: BANG!
Balance in the Sun

In the case of the Sun, the situation is quite similar, except that one of the forces is very different.

The force that would cause expansion of the Sun arises of course from the pressure of the gas of which the Sun is made.

The force that would cause collapse is gravity: remember that the Sun ($2 \times 10^{30}$ kg) is nearly a million times as massive as the Earth ($6 \times 10^{24}$ kg), so gravity is a very serious contender.
Over time, conditions within stars do change. They age, just as balloons do.

Some stars lose material to the extent that their internal pressure drops. These stars shrink to dwarf size. *(Learn more about this in the Unit *Exploring Stars and the Milky Way*.)

Other stars go the other way: they accrete material and become too hot, under too much pressure, and go nova.

*The reality is much more complicated … this too will be explained in detail in *Exploring Stars and the Milky Way*.*
Here is an image of the M4 cluster as seen using an Earth telescope. Note the tiny area marked by the white lines and the white square.

Here is a view of that tiny area as seen by the Hubble deep space telescope. The stars marked with circles are white dwarf stars... where gravity “won”.
Our Sun at present

You will be relieved to know that our own Sun is expected to remain quite stable for the next 5 billion years or so.

That leaves plenty of time to solve the many riddles remaining about the Sun’s interior, as well.

We’ll meet a few as we now follow the surprisingly long path of a photon from the core of the Sun to its atmosphere (in which the Earth is one of the bodies at which the photon may meet its final end).
A Photon’s Birth

The photon we will follow is born in the heart of the Sun, in a region of extreme temperature and pressure (at least 8 000 000 K, and density 160 times that of water). Under these conditions, p-p fusion occurs.

Four protons under enormous temperature and pressure ... pp-chain ... form a helium nucleus, a positron, a neutrino and a photon
The energy of the photon produced as a product of this fusion is $0.43 \times 10^{-11}$ J; this means that it is “hard” radiation, in the gamma-ray region.
A Photon’s Infancy

The photon is, however, in a very, very dense material. It hardly goes a fraction of a millimetre before it will be absorbed by a nucleus and re-emitted, possibly as part of a group of products of the interaction.

During this process, which can take hundreds of thousands of years, the effective speed of the photon is very, very low and its energy is depleted slightly during many of the interactions.
This means that the photon’s energy goes down as time passes. It may move from being a gamma ray to being an X-ray, then into the ultraviolet, the visible or even beyond.
Random rules...

Because photons will experience a different set of random adventures (or misadventures) during their journey towards the surface of the Sun, they acquire a wildly varying range of energies. Most will devolve into a number of lower-energy photons.

A group of p-p photons at birth: identical

The same group later on: more photons, mostly with lower energy

We don’t actually see any of this, however, as on Earth we only receive radiation that makes it right through all of the regions and into the Sun’s atmosphere.
The Journey Outward

In the core region and in the radiative region surrounding it, photons travel by radiation (from particle to particle, with a lot of interaction).

Nuclei and other particles - especially ones as active as those in the core - will emit photons in random directions.

So the photons spread outwards from the core, just as a group of active children will spread out in a playground.
The Core and the Radiative Layer

Even though they still technically make up a gas, in the heart of the Sun the particles are too tightly packed to do anything but jostle each other (like a crowd of football fans at its peak).

Energy is passed by radiation: photons are handballed from one particle to the next.
The Convective Layer

Further out, the material of the Sun is thinner and currents can begin to flow in the gas. This is called convection.

It is like the football crowd when it thins out a bit: streams of people can be seen heading for the car park, carrying things with them.

In the Sun, the hotter gas forms complex currents and eddies that carry energy upwards, while any cooler gas sinks back towards the core.
Almost to the surface

While in the convective layer, energy is transported by being “carried” by moving particles that are still pretty densely packed.

If a photon is re-emitted by an atom while within the convective layer, it is almost immediately absorbed by another and does break free from the convective layer.

Gotcha!

Rats...

Free at last!
The Photosphere

At the very top of the convective zone, however, where the surface bubbles like boiling porridge in an effect called “granulation”, the photons do have a chance to escape.
The Photosphere

These photons at last may be observed outside the Sun, so the region they come from is called the photosphere.
The Chromosphere

Above the photosphere, the first region of the Sun from which visible light can escape, is a region which starts out relatively cool: about 4,000 to 10,000 K.

This is called the chromosphere, as it can be seen during lunar eclipses of the Sun as a pale pink rind just above the photosphere.
The Corona

The uppermost layer of the Sun is called the corona, a name meaning “crown”.

You can see why from the picture above: irregular, turbulent blasts of radiation and hot gas (the “solar wind”) constantly boil into space - which make total solar eclipses so spectacular.

*This is a composite photo: the black ring shows where the image is missing.*
The Solar Atmosphere

The upper regions of the Sun make up what is called the “atmosphere”.

- the photosphere
- the chromosphere
- the corona

4,000 to one million degrees K

The rise in temperature moving out from the chromosphere and into the corona is surprising: you’d expect things to get cooler as you moved away from the Sun’s core. This rise is believed to be due to magnetic effects, but is not yet very well-understood.
New information is being obtained about the Corona. This image of coronal loops, indicative of strong magnetic fields, was taken by the TRACE satellite on November 6, 1999. Studies of such data will help determine the origin of coronal heating.
How do we measure this stuff?

Most of our information comes from the photosphere, as that’s where visible light leaves the Sun.

Let’s have a closer look at what we receive on Earth, and why, and what information we can glean from it.
Absorption spectra

Photons are generated in the core of the Sun, and by the time they reach the photosphere they are a very mixed bunch indeed for reasons that we have seen.

However the nuclei in the photosphere pick them over, absorbing only those with very specific energies ...

You’ve got just the right energy, so I will absorb you...

... but you guys haven’t, so I’ll let you pass

Where’s your mate?

He was absorbed...
The result on Earth

The light that enters the photosphere has a spectrum typical of “black body radiation”, a range of wavelengths and intensities as shown at right.

If the light is spread into a “rainbow” (for instance, by passing it through a prism) then there is a smooth graduation from one colour to the next, as above.
Although the spectrum of light that entered the photosphere was smooth and complete, some wavelengths are missing when it emerges (and is detected).

These *absorption lines* come about because the nuclei in the photosphere have taken photons of very specific energies from those that passed them on their way out of the Sun.
A Useful Fingerprint

Each particular type of nucleus will absorb light only with certain preferred wavelengths, leaving gaps in the spectrum. It is as if each element has a distinctive fingerprint that it leaves on light that passes through it. This is very, very useful as it allows astronomers to work out which elements are present in a gas (such as the photosphere of our own Sun and other stars).
Over 20,000 absorption lines have been identified in the solar spectrum from the photosphere.
Finding temperature from spectra

The overall shape of the spectrum from a star can indicate its temperature. The hotter the star, the more light it emits at the blue, short-wavelength end.

- **hot star**
- **medium star**
- **cool star**

Flux vs. Wavelength

- Ultraviolet, X-ray, gamma ray
- Visible light
- Infra-red
Three types of spectra

• The first spectrum that we looked at was the absorption spectrum: the result of passing light through a gas which absorbs some of it.

• The second spectrum was the continuous spectrum, the shape of which can indicate temperature.

• The third type of spectrum used in astronomy is the emission spectrum: the light observed when an object emits light (usually when it’s pretty hot).

*The particular frequencies emitted by a gas will match those it can absorb: a person leaves the same fingerprints whether they are leaving gifts ... or stealing!*
Summary

In this Activity you learned about the way energy is transferred from the core of the Sun to the surface.

You also learned about how measurements can be made of some of the Sun’s properties using spectra.

In the next Module we will learn about the active Sun and its effects on the Earth.
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Sun (false colour): ultraviolet - NASA
http://antwrp.gsfc.nasa.gov/apod/image/9701/bluesun_soho.jpg

The Earth from space - NASA
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Saturn and its rings- NASA
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Supernova - NASA
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Sun in Helium light from the chromosphere - NASA
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The solar corona - NASA
http://antwrp.gsfc.nasa.gov/apod/image/9702/solwind_soho.gif

Coronal Loops - TRACE
http://vestige.lmsal.com/TRACE/Science/ScientificResults/TRACEclimage1.jpg
Now return to the Module home page, and read more about the Sun in the *Textbook Readings*.

*Hit the *Esc* key (escape)*
*to return to the Module 20 Home Page*
What’s the difference? ... Radiation

**Radiation**
Radiation is the transport of energy by direct “beam”: some kind of radiation (usually massless and most frequently electromagnetic, such as light) travels directly from one object to another, carrying energy with it. Radiation can occur in a vacuum. It requires no intermediary material.

**Convection**

**Conduction**
What’s the difference? … Convection

Convection is the transport of energy by “carrier.”

The carrier might be an atom or molecule of gas or liquid, or a particle in plasma.

There will of course be lots of convection in those parts of the Sun where particles are very free to move.
What’s the difference? … Conduction

Radiation

Convection

Overall movement

Conduction

Conduction is the transport of energy when it is passed along from atom to atom or from molecule to molecule in a solid.
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