

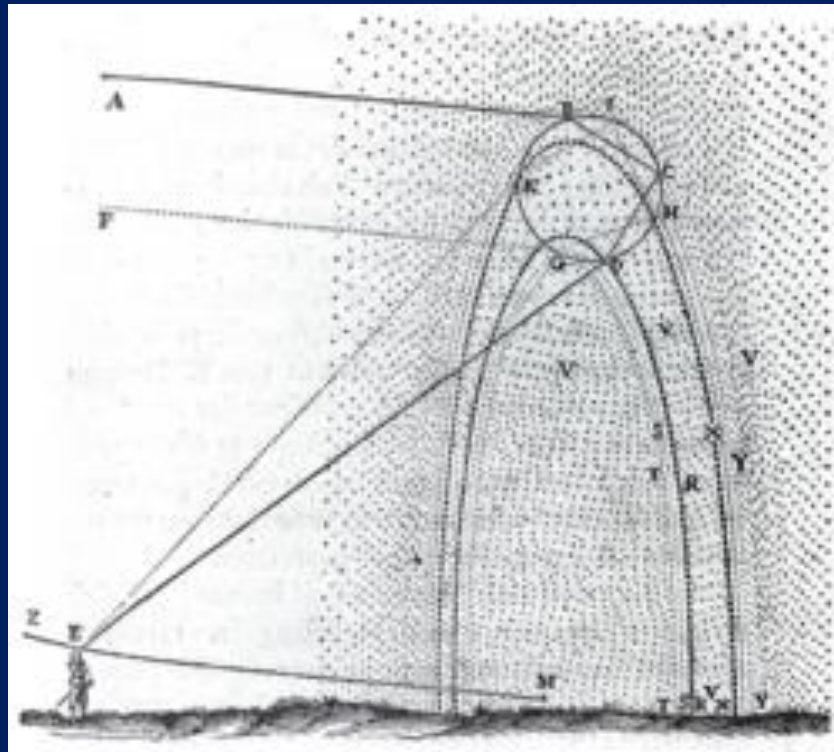
Rainbows, Halos and Glories – colour and light in the atmosphere



By Dr Fred Stevenson

DESCARTES 1637

Rainbows require sunlight and raindrops. Their circular arc does not appear to depend on the size of the raindrops – Descartes concluded that light travelled through spherical droplets as follows:



The way light travels through the droplets of water requires an understanding of the laws of reflection and refraction.

The Law of Reflection of Light

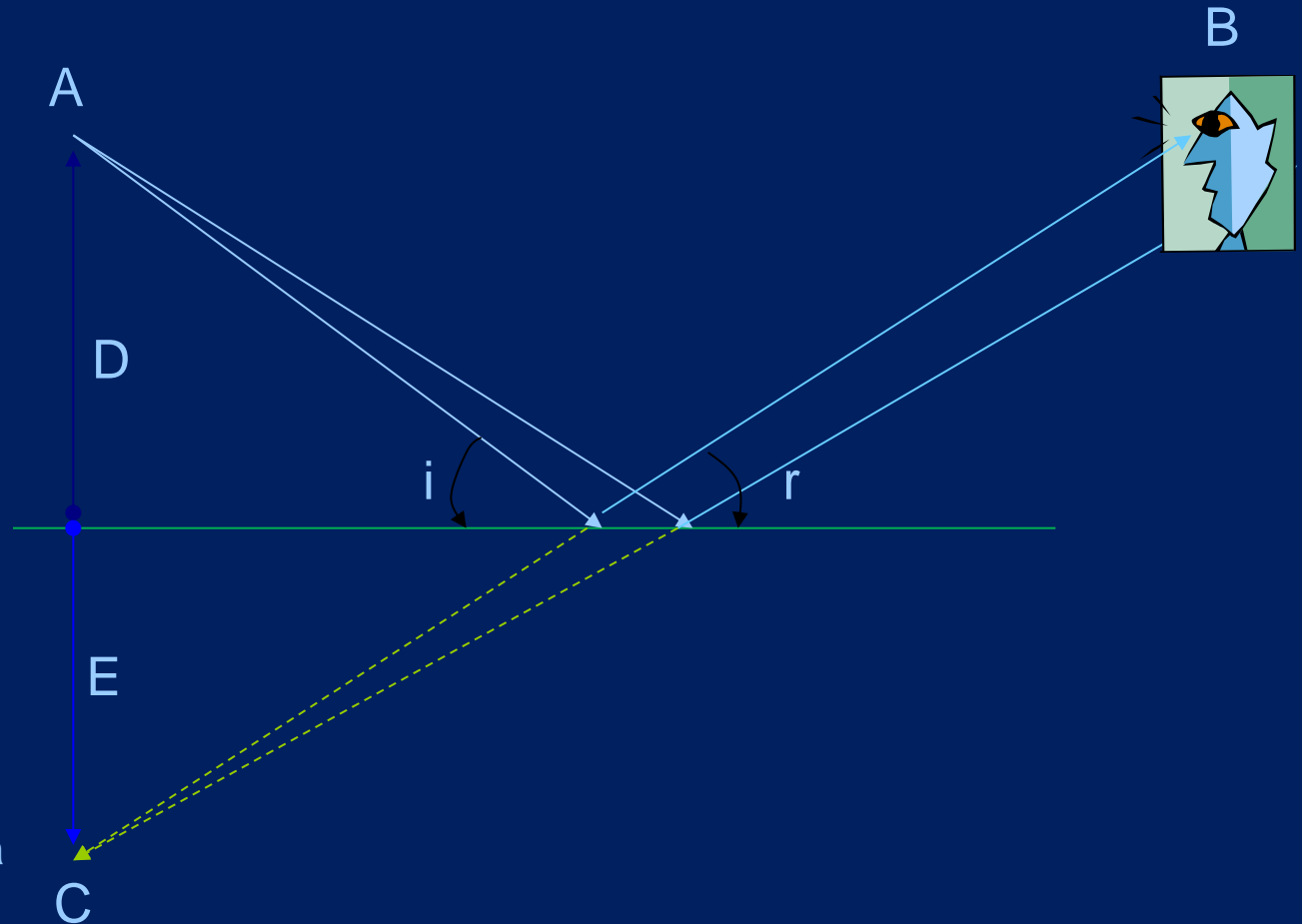
Angle of incidence, i = angle of reflection, r

$$i = r$$

Observer at B will see an image of A at C and D at E.

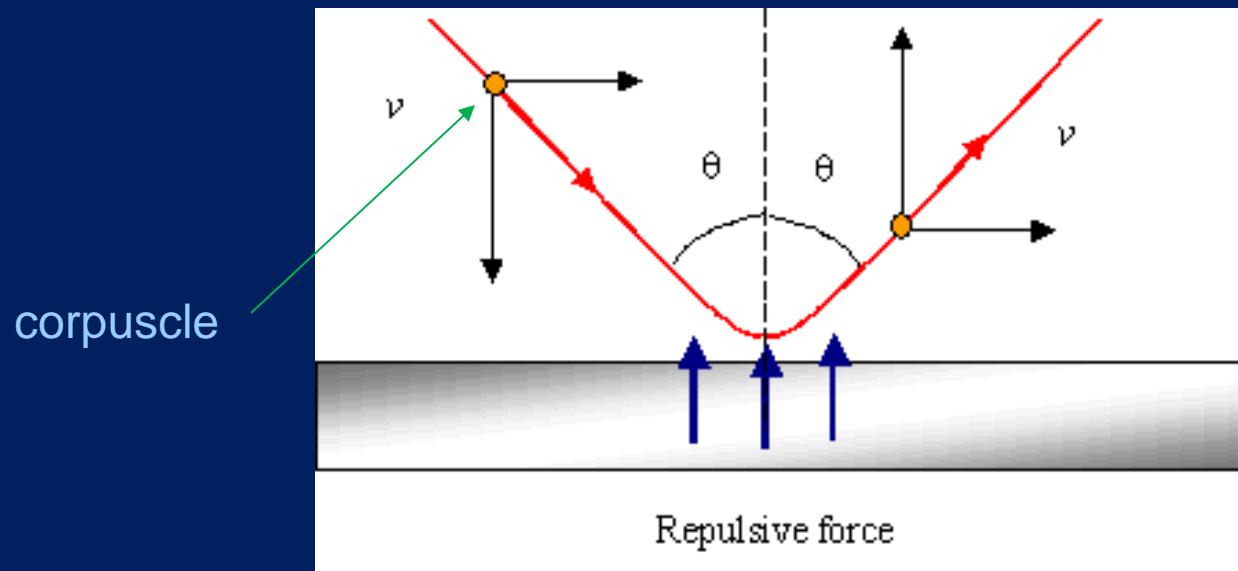
Images of objects in a mirror appear to be an equal distance behind the mirror as the real objects are in front of the mirror.

This explains why images are reversed left to right, but not top to bottom! (for a vertical mirror)



Light allows us to see our environment through our eyes. Light appears to be emitted by certain objects and reflected by others - but what is light made of?

Newton - 1660s - the corpuscular theory of light.



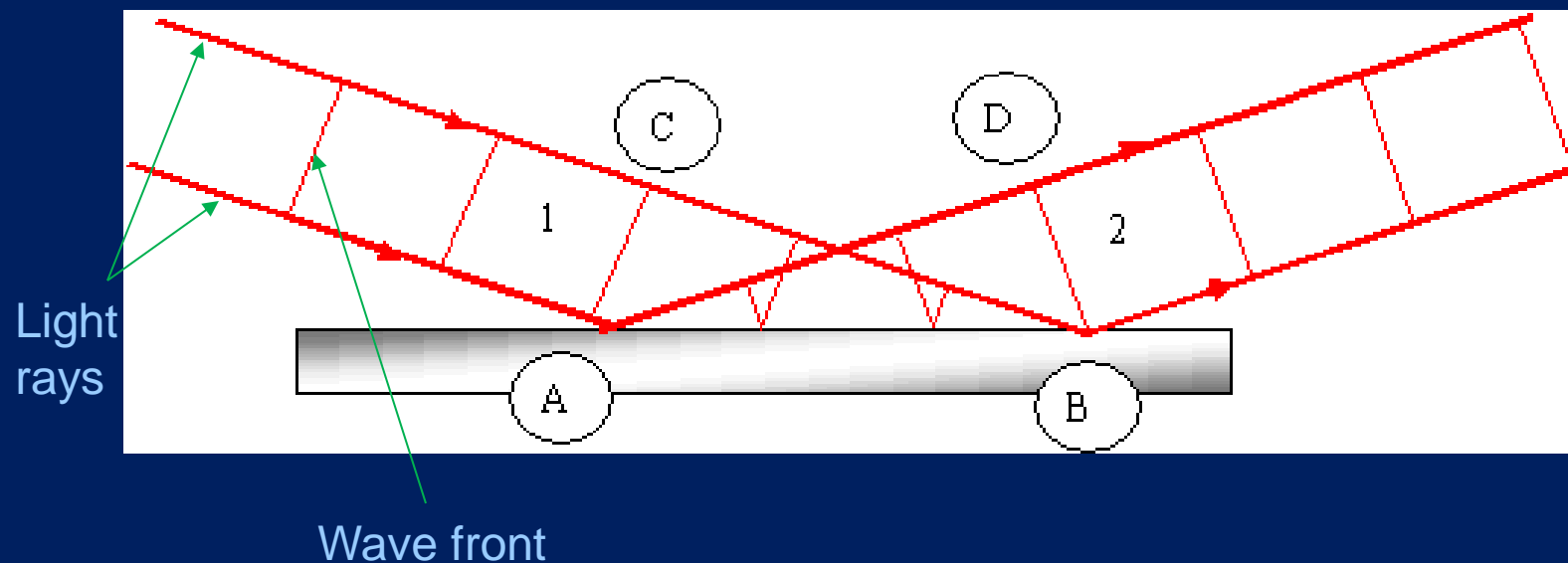
Explained the law of reflection:

angle of incidence = angle of reflection

The alternative - the wave theory of Huygens

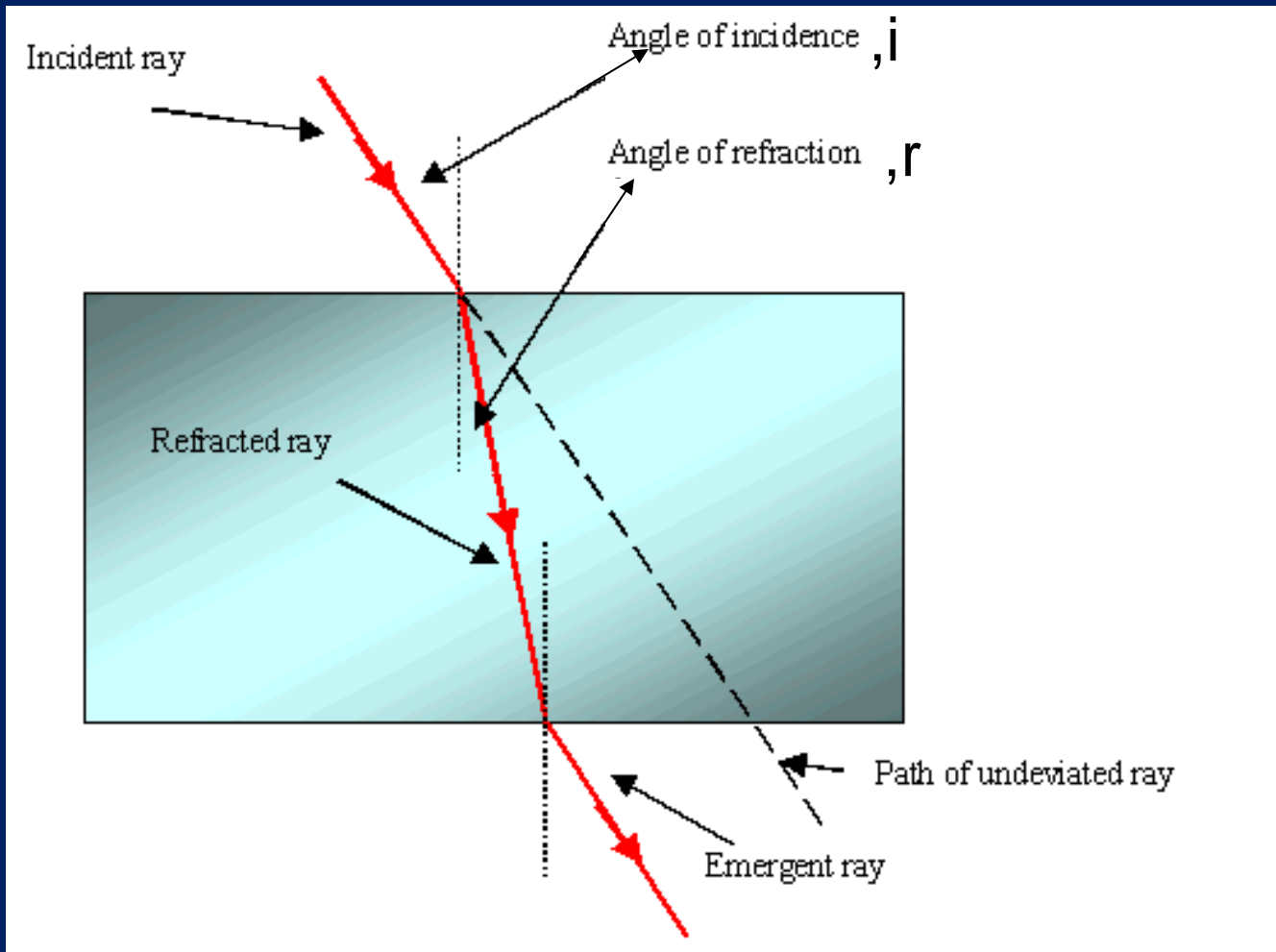
Light is made up of energy waves that travel much like water waves.

Huygens' explanation of reflection.

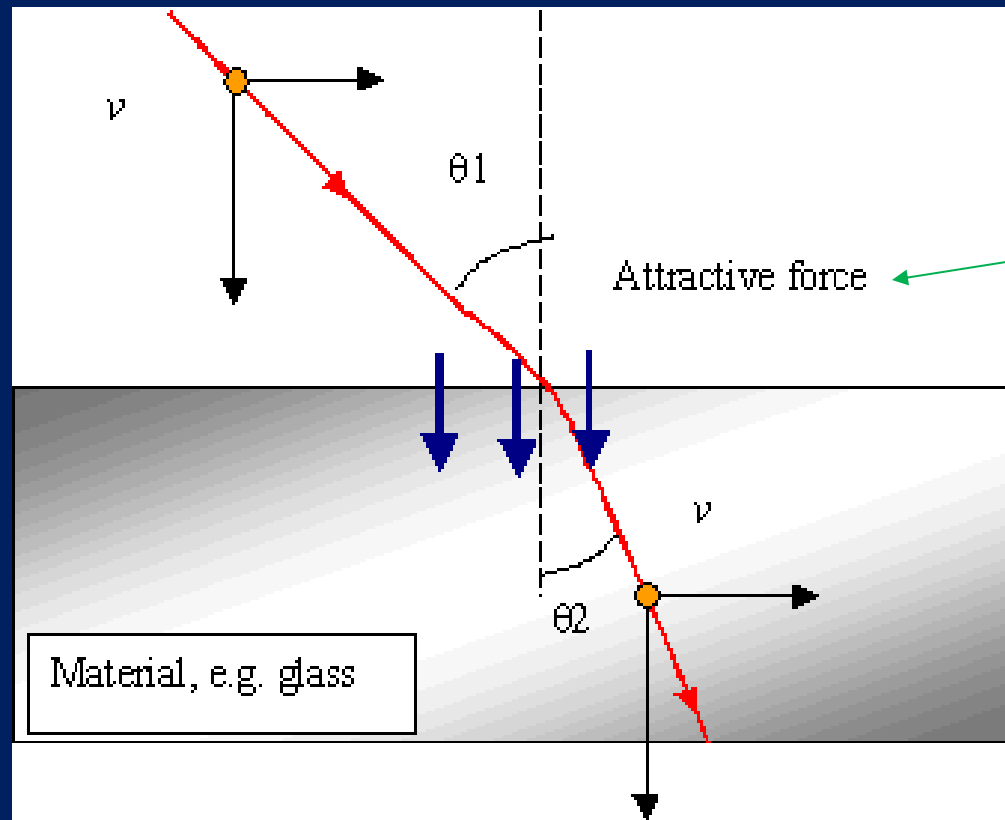


The Refraction of Light

The change in direction of a ray of light as it passes from one medium to another.



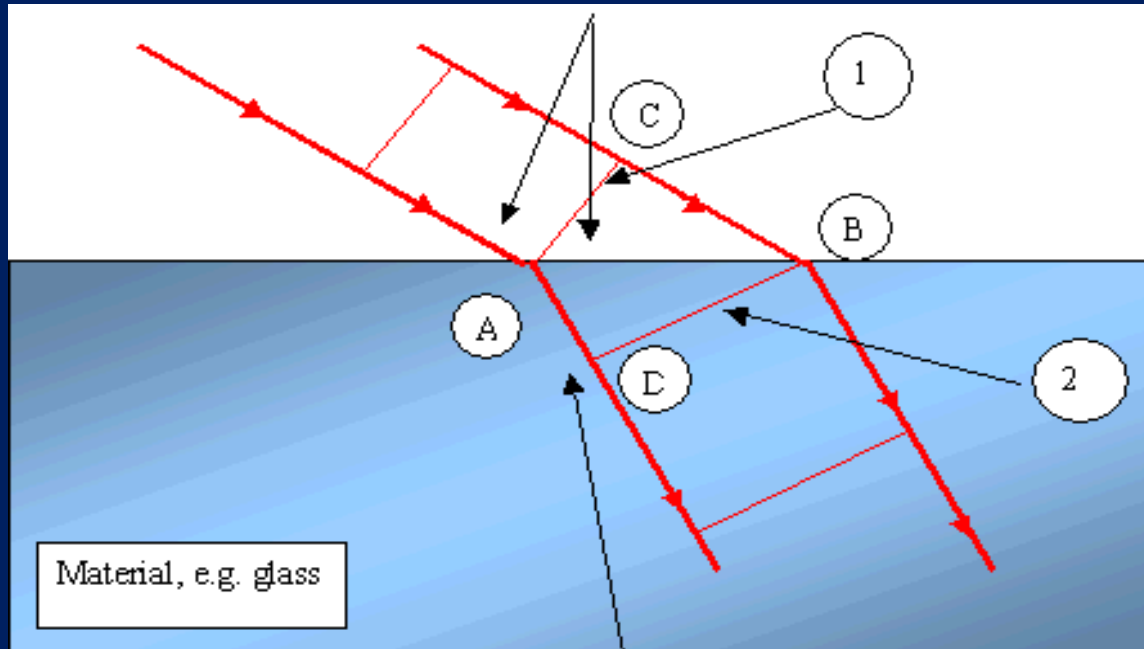
Newton's explanation of refraction



Causes the velocity to increase downwards

Prediction - velocity of light in denser medium is greater than in air.

Huygens' explanation of refraction – using the wave theory of light (late 17th century).

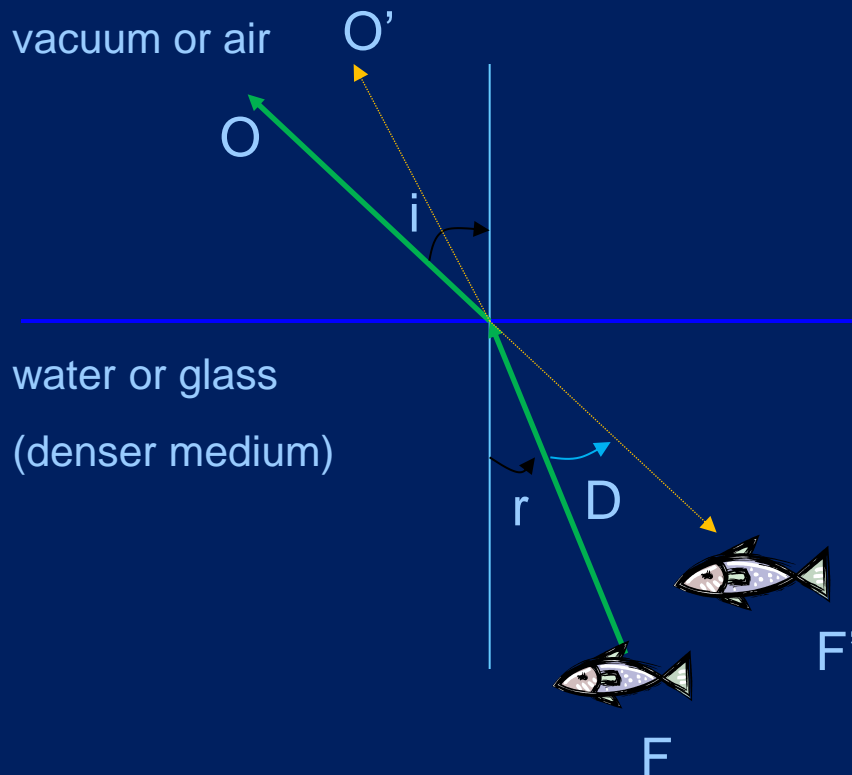


As wave crest AC enters medium it slows and becomes DB in the medium.

Prediction - the velocity of light is slower in the denser medium. This was found to be correct so Huygen's theory was accepted over Newton's corpuscular theory.

REFRACTION

When light travels from a less dense into a denser medium its path is bent towards the 'normal' - the line perpendicular to the surface.



Light travelling in the reverse direction follows the same path :

The law of the reversibility of light.

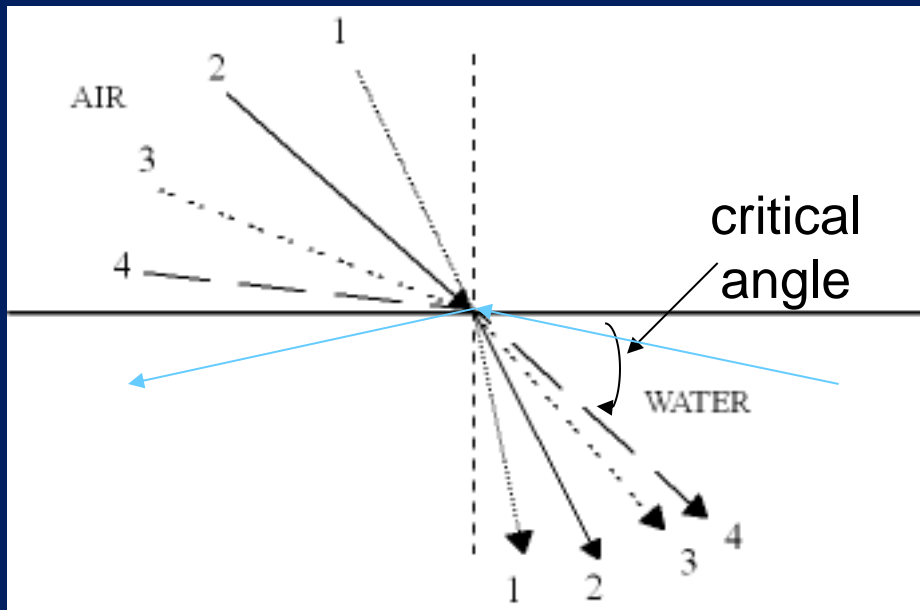
If a fish is in the water at F it will appear to an observer at O to be at position F'.

Its position is 'lifted' by an angle D (deviation) where $D = i - r$

Alternatively from the fishes perspective the observer will be seen at elevated position O'.

The formula relating the angle of incidence, i , to the angle of refraction, r , is given by: $\frac{\sin i}{\sin r} = \text{constant} = \text{the refractive index} - \text{Snell's law.}$

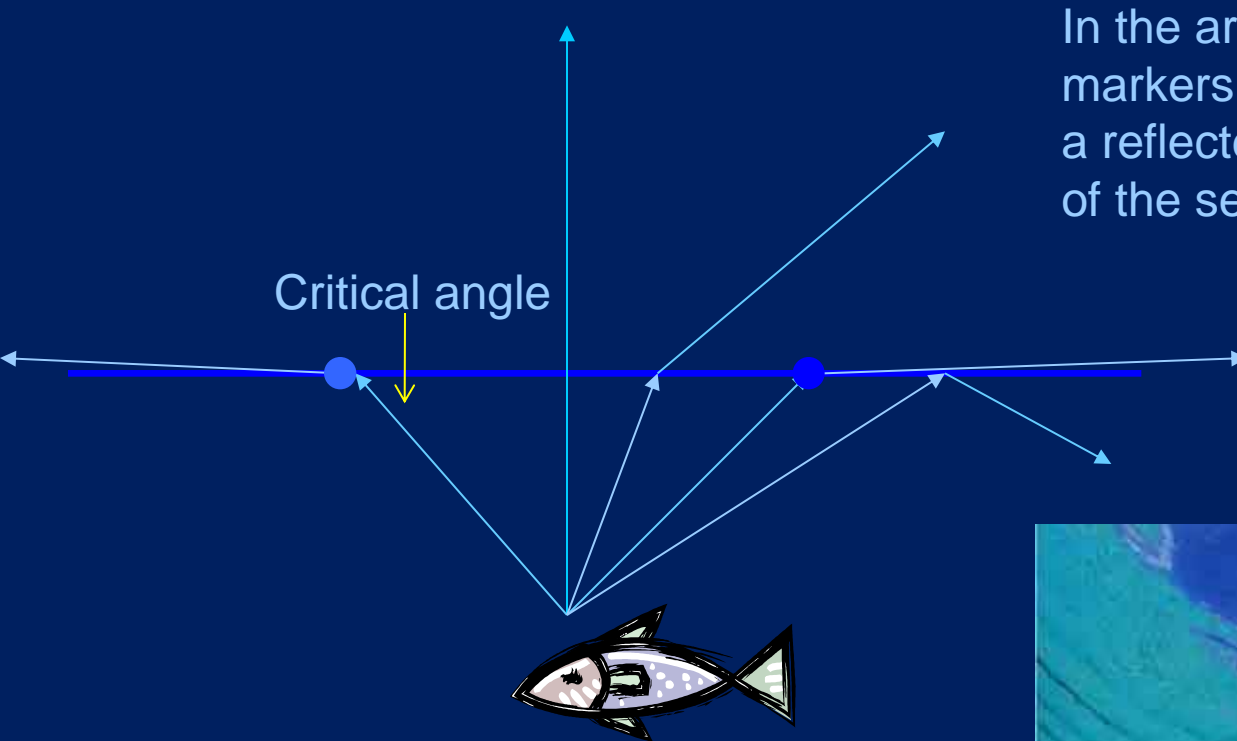
If we increase i to its maximum of 90° (just skimming the surface = ray 4) we find that r has an angle of $\sim 46^\circ$ - the critical angle.



Because of the reversibility of light a ray hitting the surface *from below* at the critical angle will come out skimming the surface.

If this angle is made any shallower (blue ray) then the ray reflects off the surface back into the water - **total internal reflection**.

When fish/divers look up they see the whole sky filling a circular area above them - **the optical manhole**.



In the area outside of the blue markers the fish / diver will see a reflected image of the bottom of the sea/pool.

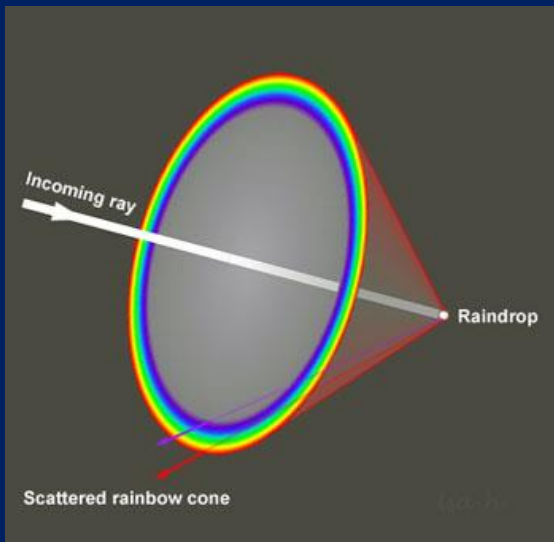
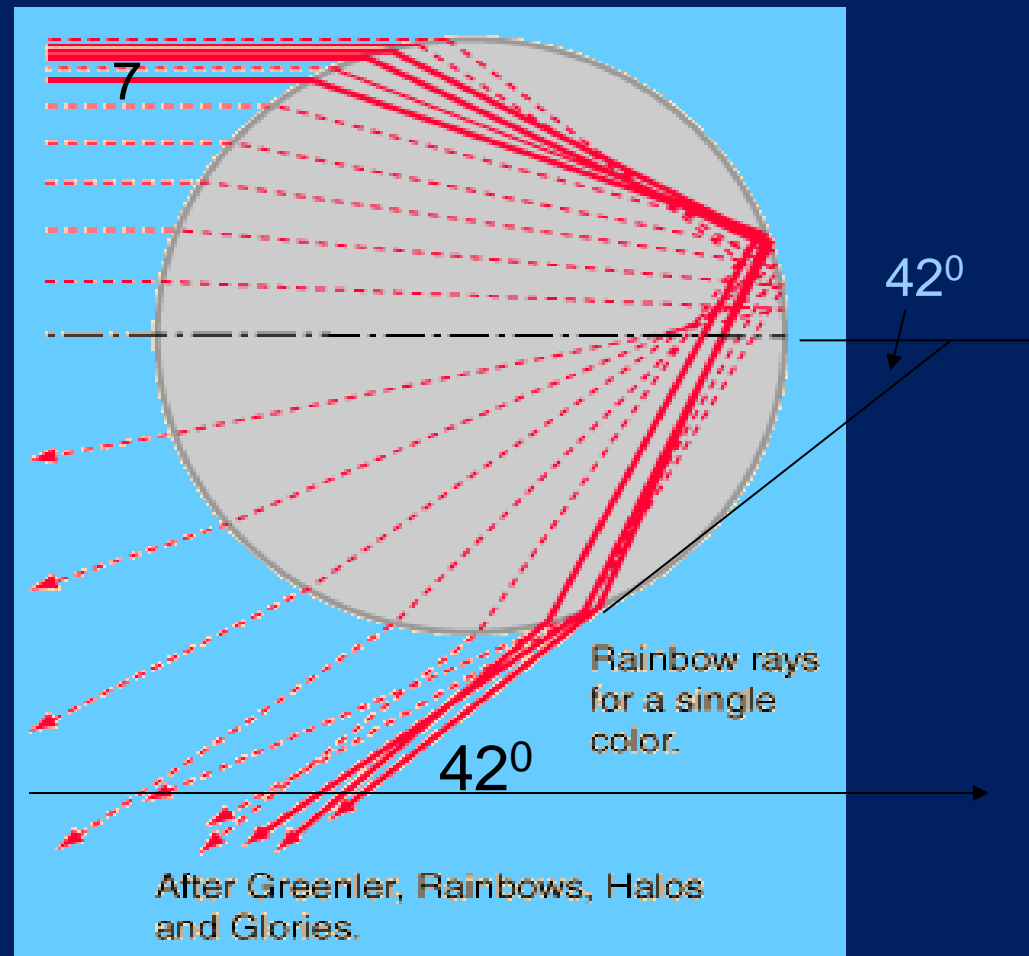


Light rays entering a raindrop from the Sun (parallel) will emerge in a cone of light.

Diagram shows light entering top half of droplet.

RAY 7 - the **Descartes ray** - leaves at the maximum angle to the horizontal.

Nearby rays leave at almost the same angle - light is concentrated in this direction - at 42° to centre line.



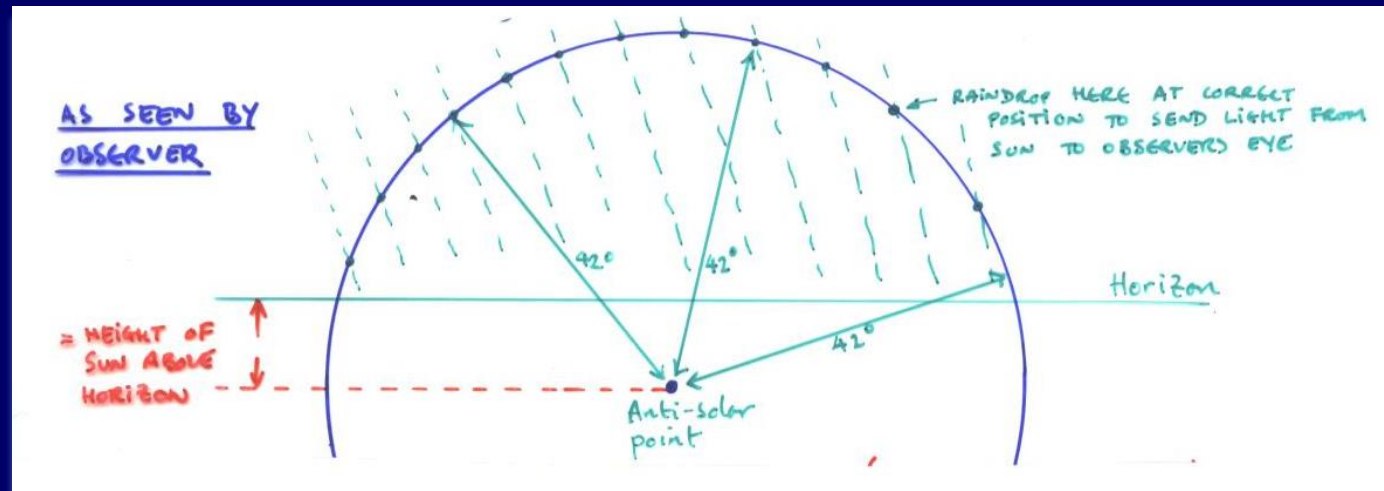
To see this light we need to look at an angle of 42° from the 'opposite to the Sun' direction - i.e. 42° from the **ANTI-SOLAR POINT**.

Why the Rainbow is Circular

The shadow of observers head is in the direction of the anti-solar point and hence at the centre of the rainbow.



Every raindrop (if in sunlight) that lies 42° away from the anti-solar point will contribute to the brightness of the rainbow in that direction i.e. the 'distance' to a rainbow is a bit meaningless. All of the points 42° away from the anti-solar direction trace out a circle around it - this is why the rainbow is circular - it is a reflection of the circular symmetry of the rain drops.



Height of top of rainbow arch above horizon

$$= (42 - \text{altitude of sun})^\circ$$

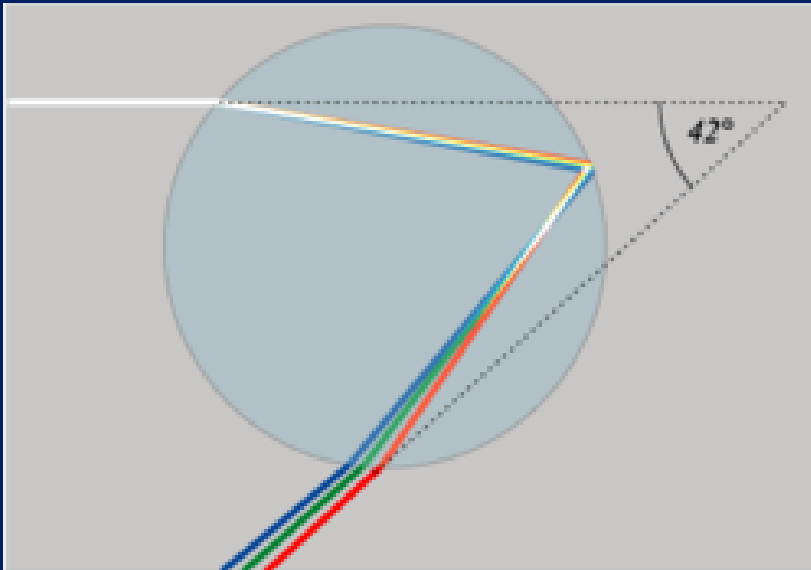
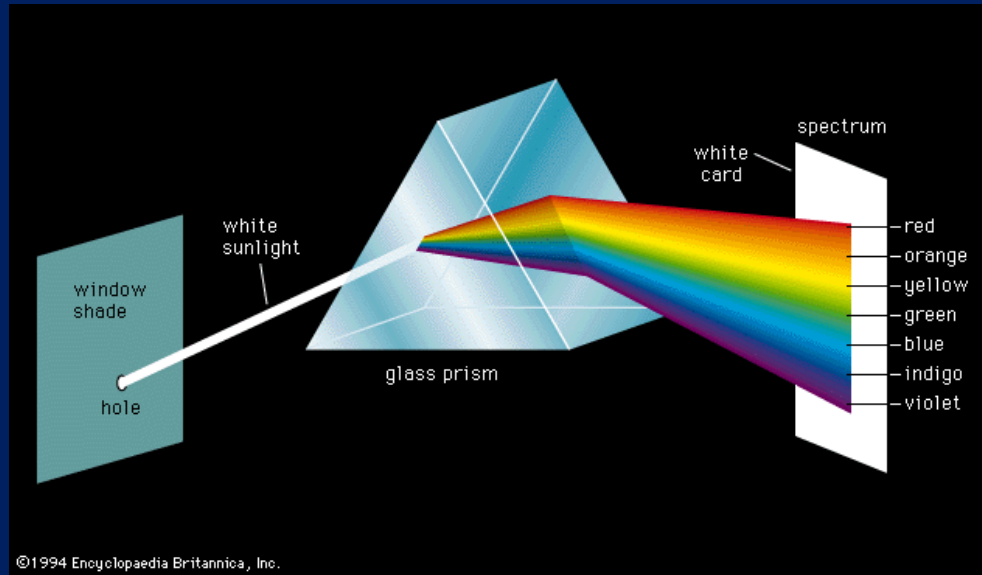
Rainbows are therefore most easily visible if the sun is low in the sky.

RAINBOW COLOURS

Newton - prism - white light is made up of a mixture of different colours

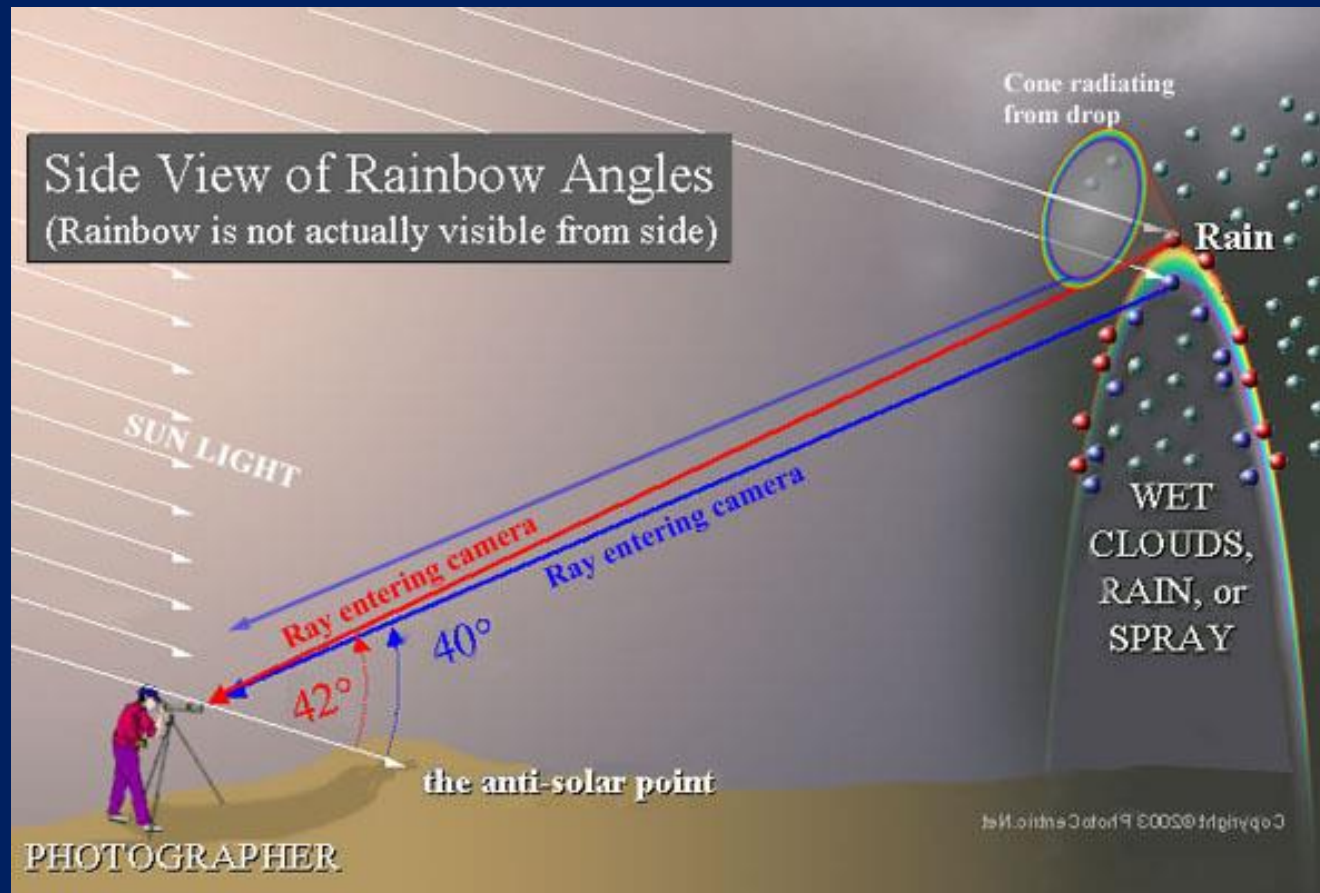
The amount of refraction depends on the wavelength of light.

Blue - shorter wavelength, λ - bent more than **Red** (longer λ).



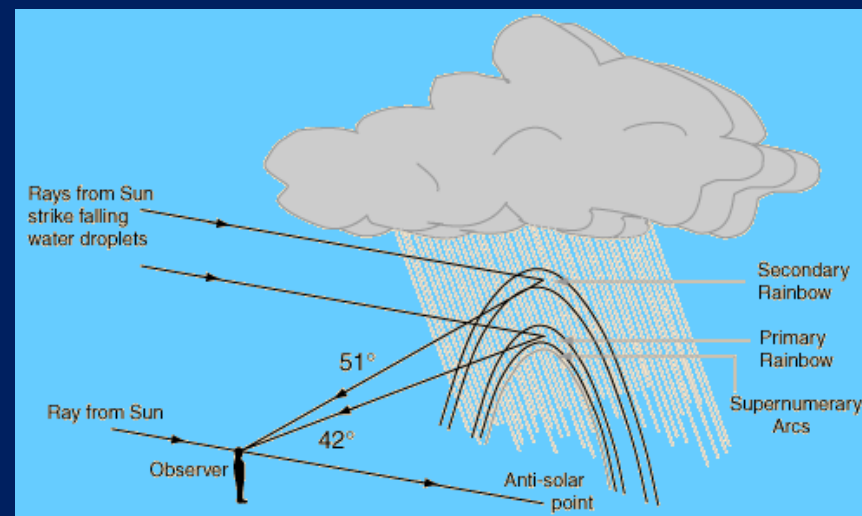
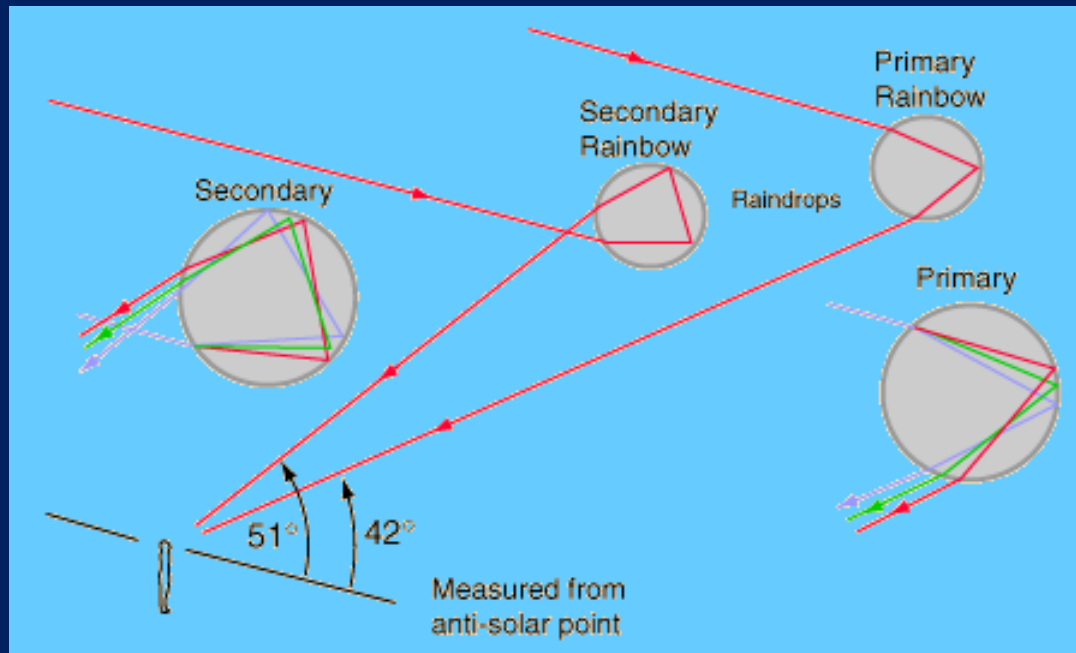
Blue light is deviated from the sun's direction by the greatest angle – hence it has a smaller rainbow angle (40°) than for red light - so we see **red on the outside** of the rainbow and blue on the inside.

The anti-solar point is marked by position of the shadow of the observers head (more accurately eyes!)



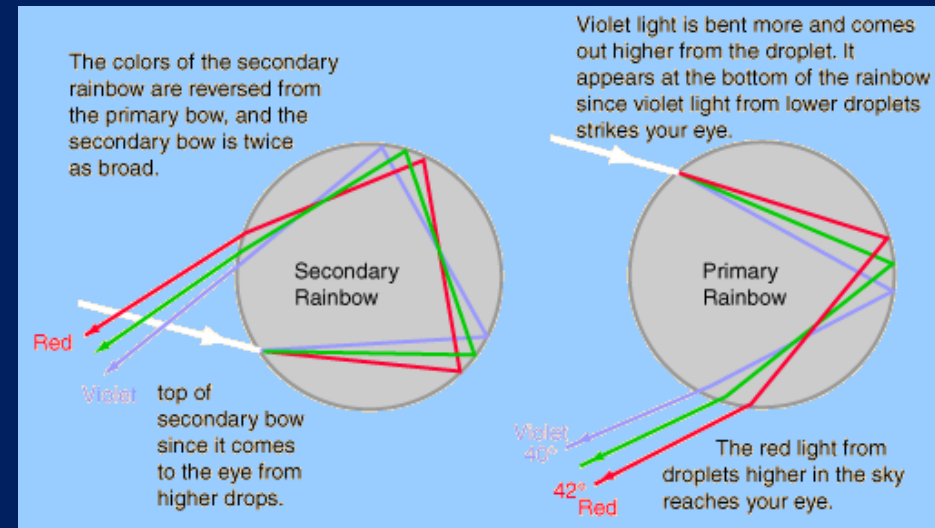
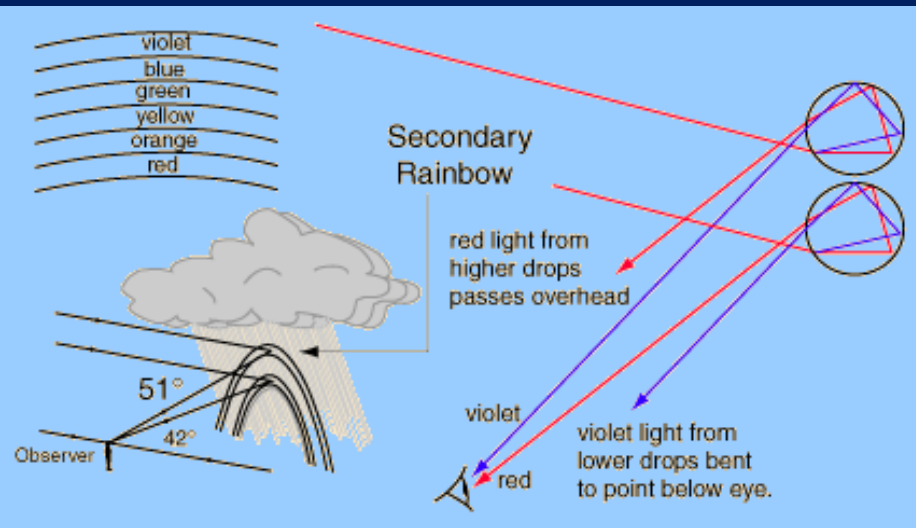
All drops in sunlight 42° away from the anti-solar point contribute light to the rainbow as seen by the observer at O. The positions of these drops all 42° away from the anti-solar point trace out a circle in the sky.

The Secondary Bow – a second reflection is possible inside the raindrop – this leads to a fainter cone of light at 51° around the anti-solar point.



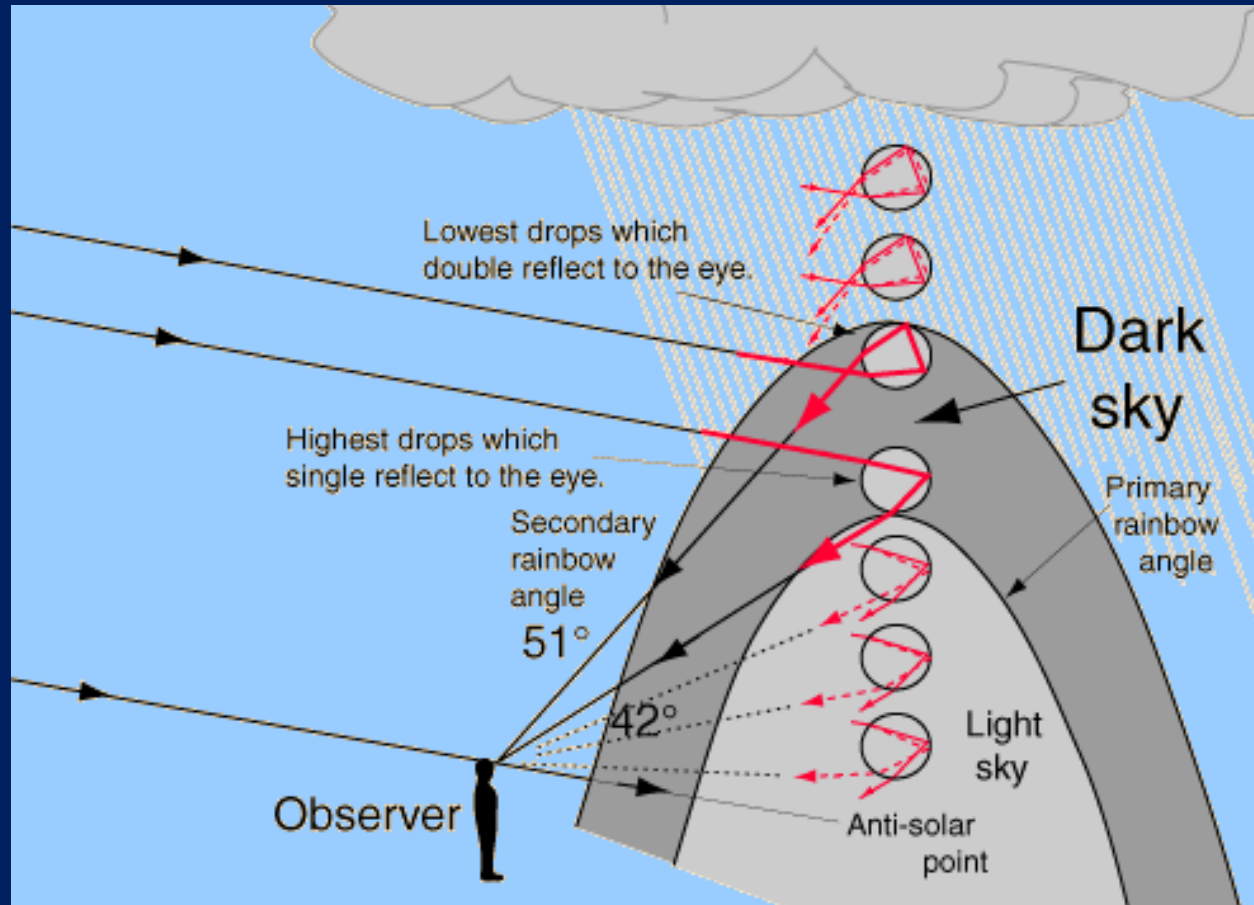
For the secondary bow the extra reflection reverses the colour order - the secondary bow has red on the inside and blue on the outside.

Different rain drops contribute to the primary and secondary bows.



Higher Order Bows – it is in theory possible to have tertiary, quaternarybows - but none have ever been seen.

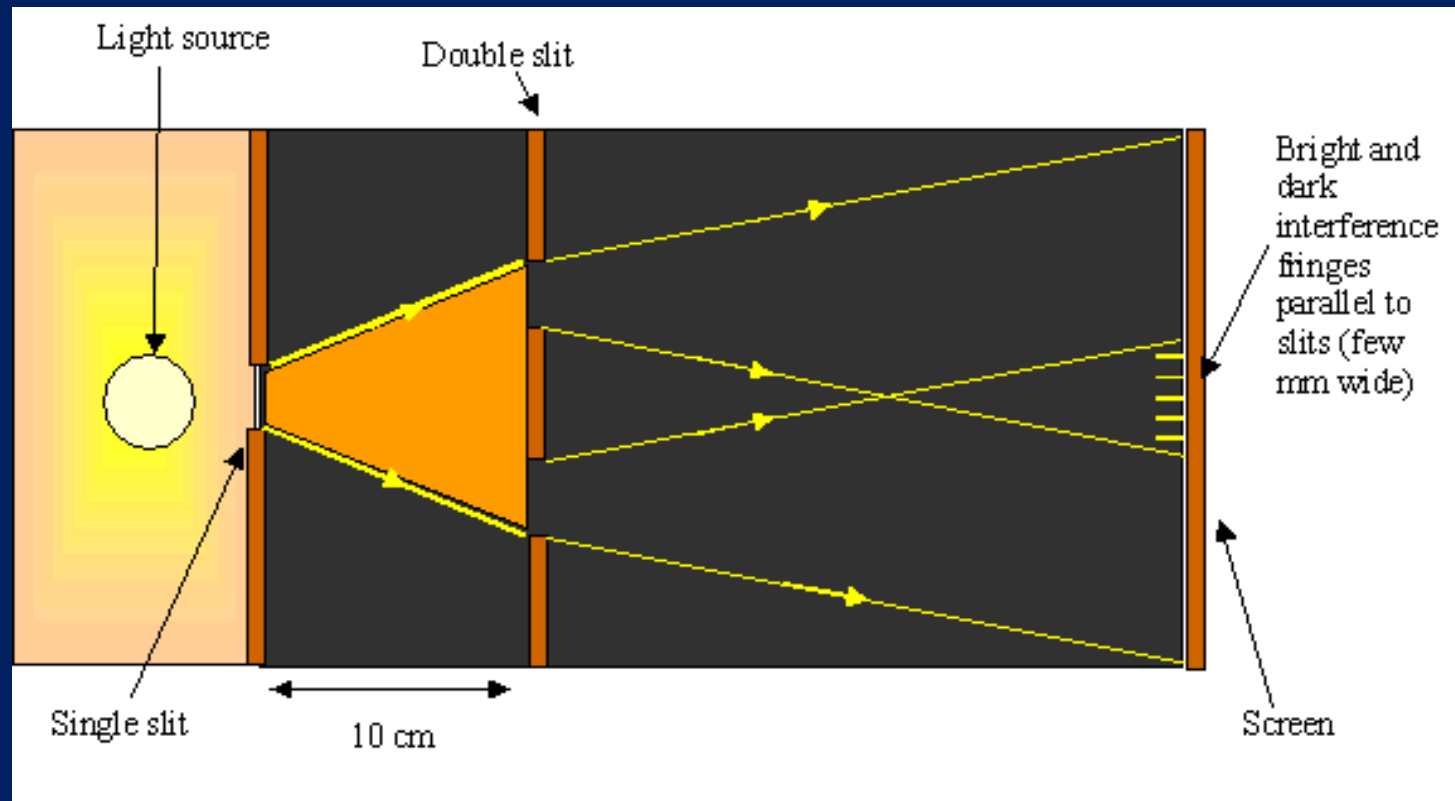
Alexander's Dark Band – between the two bows there is no returning light to the observer and the sky is at its darkest. The sky inside the primary can be quite bright.



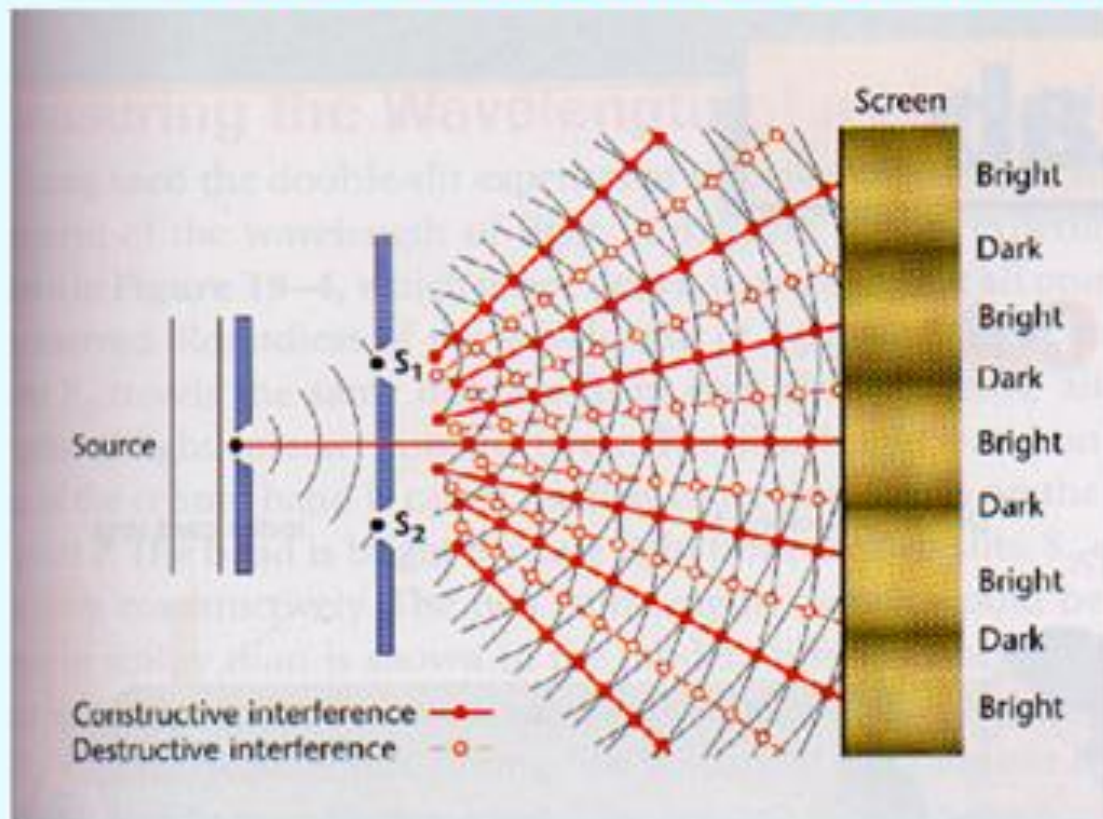


Thomas Young and the double-slit experiment (1801)

Demonstrated the interference of light from two different sources - could only be explained in terms of waves - **the phenomena of interference** had been observed in water waves for example.



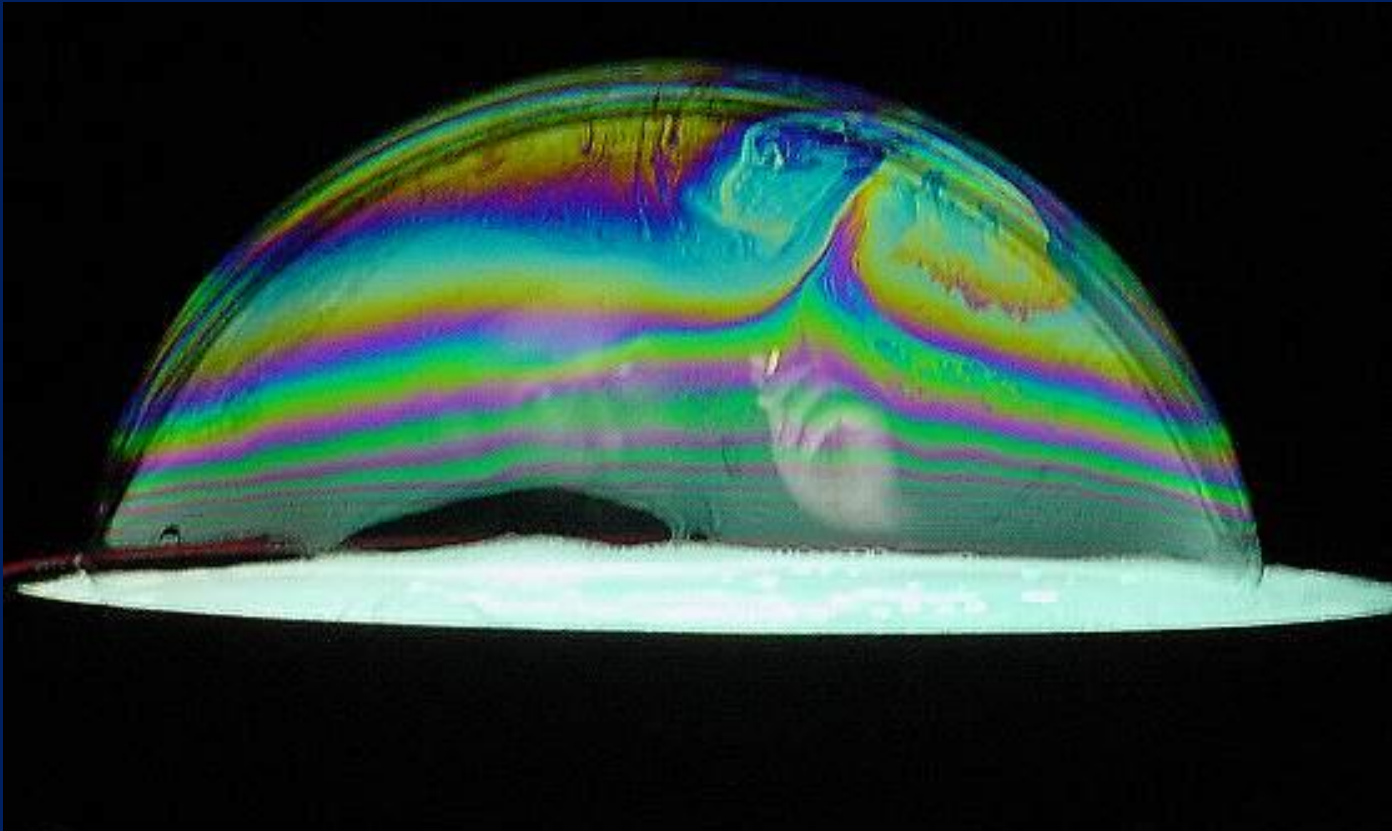
Interference of Waves



Constructive
makes bright
bands,
destructive
makes
dark bands.

Where crest meets crest or trough meets trough,
we have constructive interference.
Crest plus trough cause destructive interference.

You don't have to do complicated physics experiments to see effects of the interference of light.

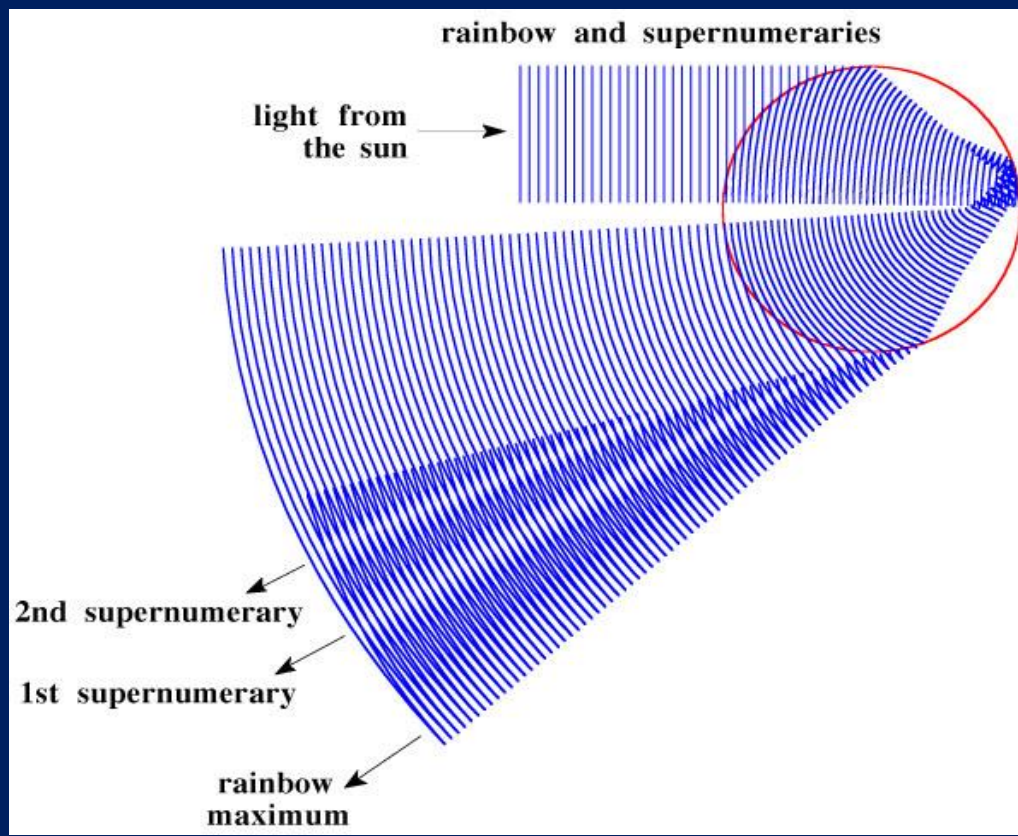


Similar patterns can be seen when light is passed through a single narrow slit - **diffraction** - which can also be explained by the wave model. This is all good evidence for the wave model of light.

INTERFERENCE / SUPERNUMERARY BOWS

Interference is another consequence of the wave nature of light.

Rays either side of the Descartes ray emerge parallel and at a smaller angle to the sun's rays - since they are parallel these rays can interfere. Therefore the supernumeraries form a series of faint bows inside the primary (or outside the secondary - very rare).



The distance between the supernumerary peaks *depends on droplet size* - smaller drops give larger spacings.

Smaller drops circular/spherical (<1/2mm)



Large drops are squashed because of air resistance (~1mm)



- they are only circular in horizontal cross section.
- they therefore contribute light mainly in a horizontal plane and therefore *make the rainbow brighter at its base*.

For similar reasons supernumeraries are brighter at their tops (larger range of contributing sizes at base blurs the supernumeraries out).

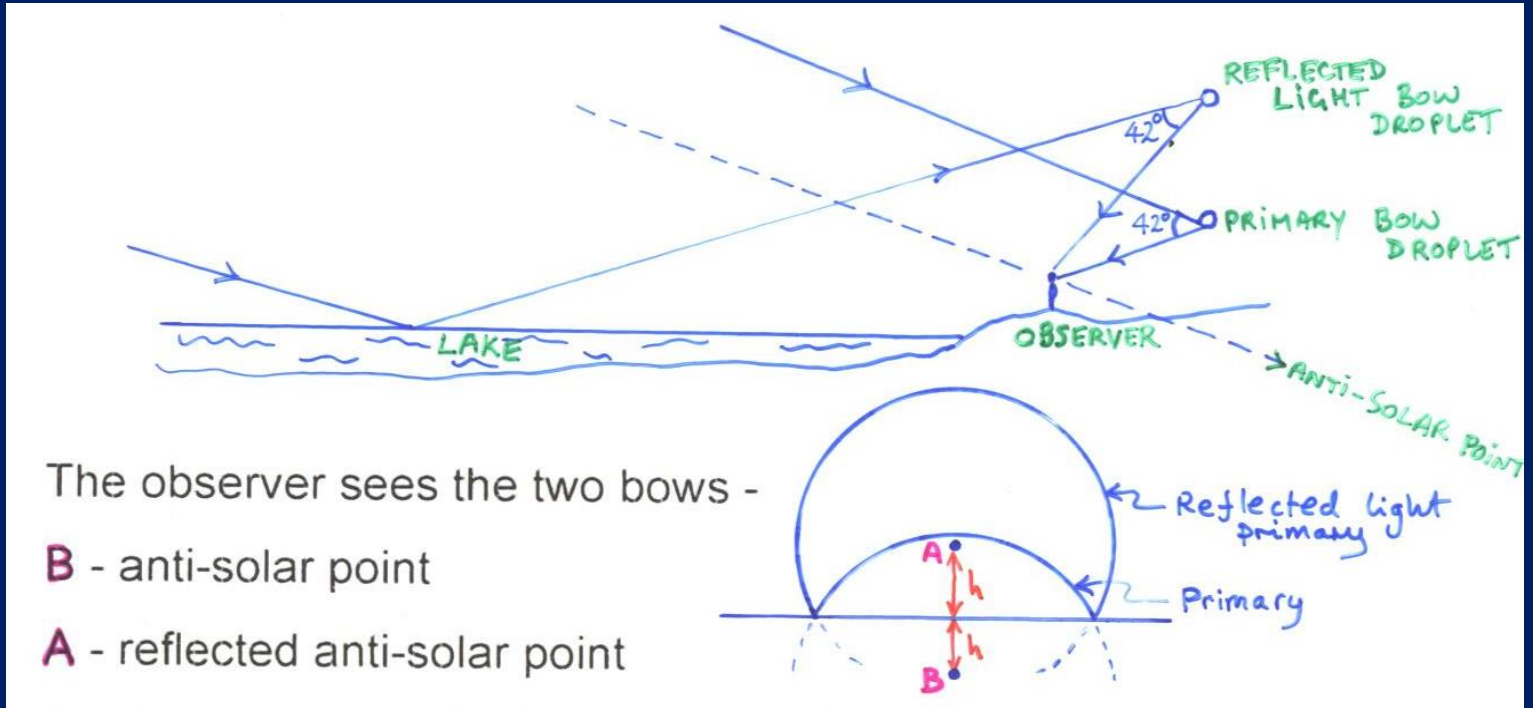
Note: raindrops are never 'teardrop' shaped!

Supernumerary bows





REFLECTED LIGHT RAINBOWS



Another way to see why there are two bows is to imagine what the observer would see if they turned around - there would be two suns!

The direct sun and the reflected image sun.

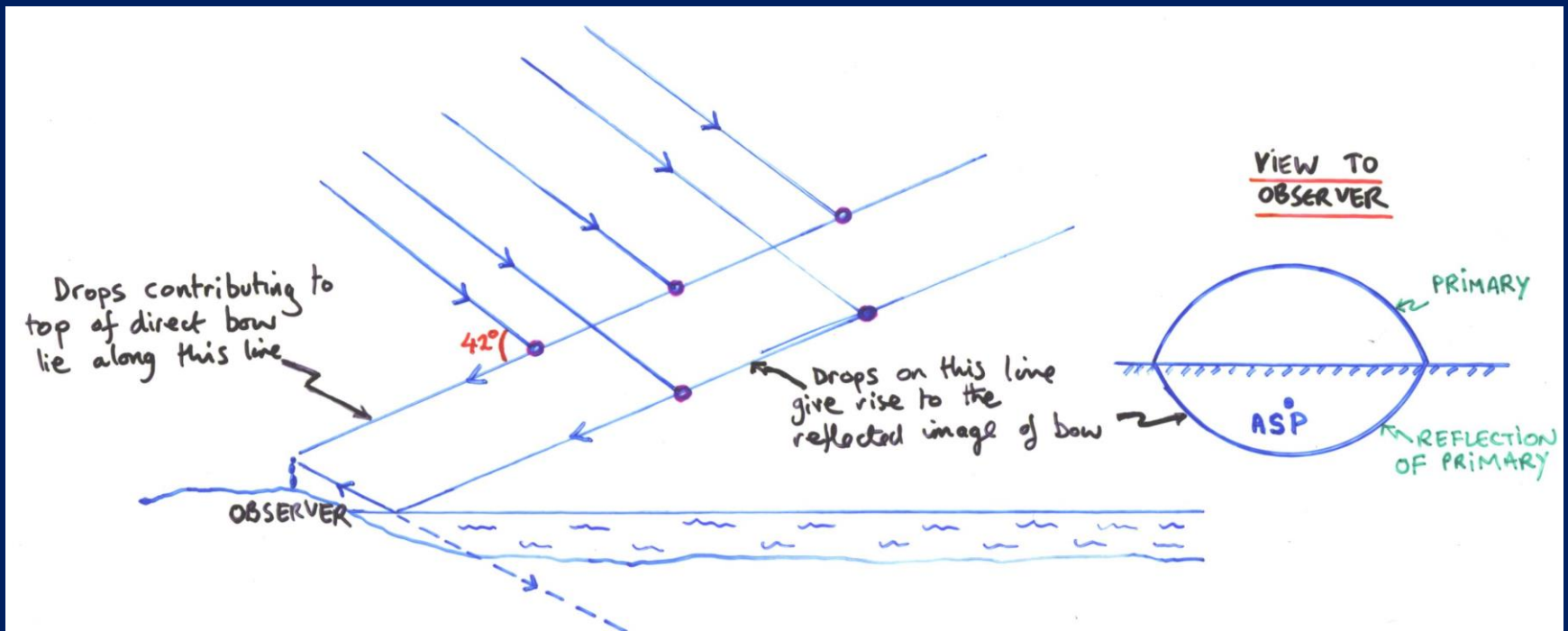
Including secondaries makes 4 bows altogether!



REFLECTED RAINBOWS

We can of course see a reflection of a rainbow in water (if the water is in front of the observer rather than behind as in the above case)

Interestingly each bow will be formed by different drops.









For very small droplets diffraction effects blur the supernumeraries and colour separation so much that the colours all overlap and we end up with a white bow or fog bow.

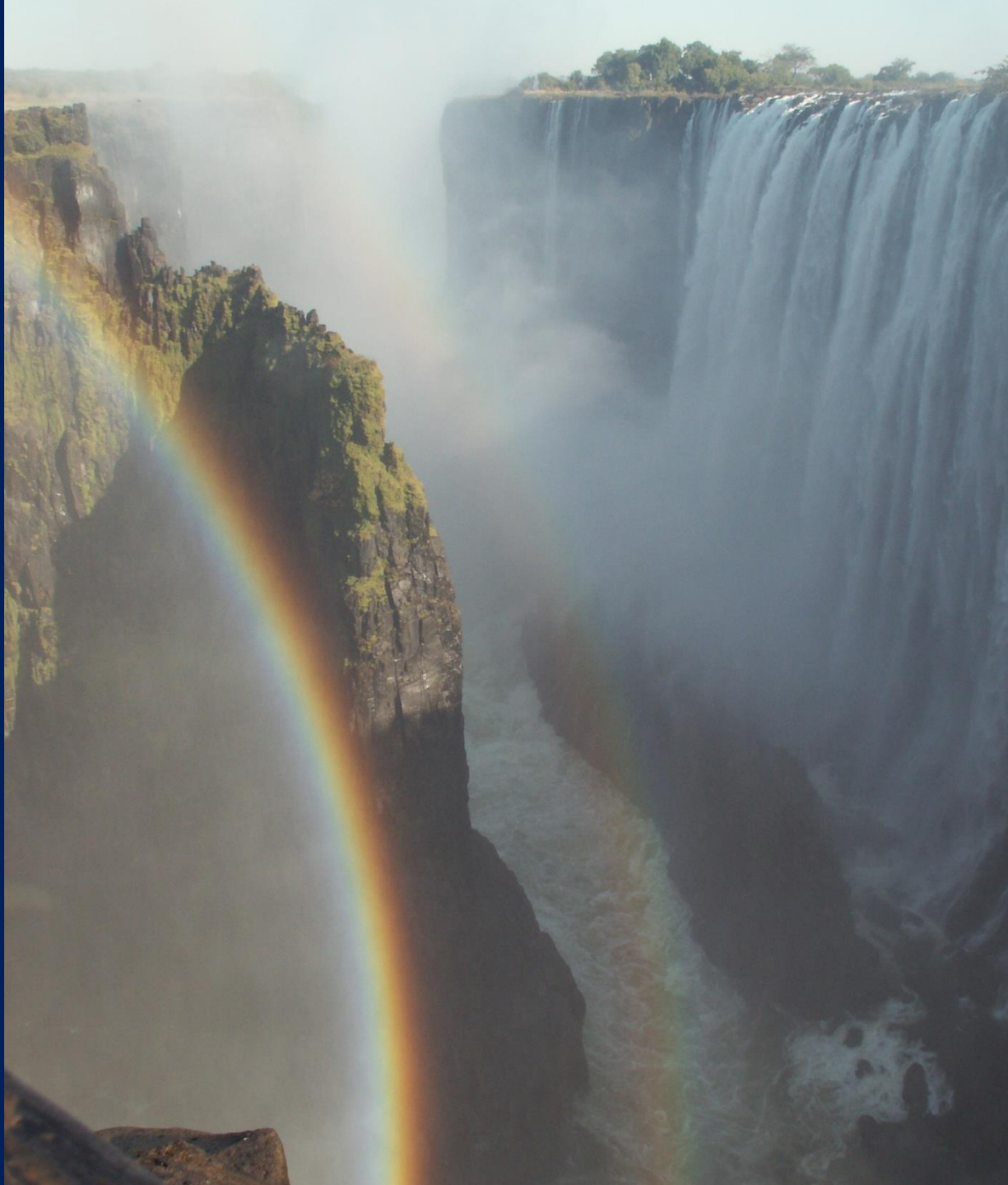


Kieth Langill



Rainbows everywhere







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© Paul Hicker



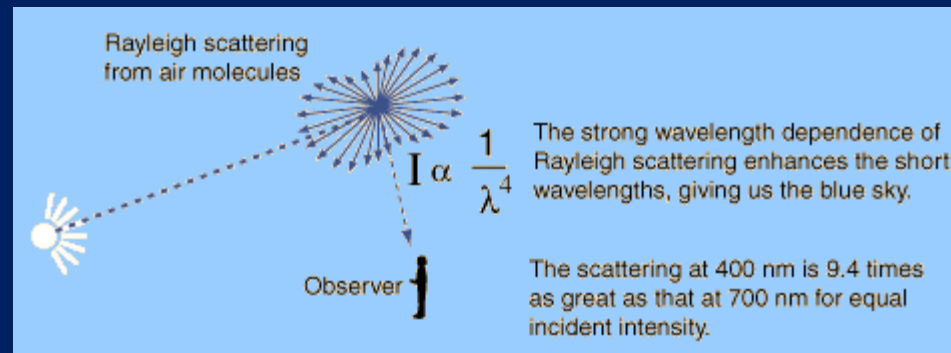
LIGHT SCATTERING EFFECTS

How waves scatter depends on the relative sizes of the scatterer and wavelength.



Large size compared to wavelength get scattering (mixture of diffraction and reflection), smaller sizes or larger λ 's give less scattering.

In atmosphere scatterers = molecules, size $\sim \lambda/1000$. For these Rayleigh showed scattering $\propto 1/\lambda^4$ - smaller λ s a lot more scattering - **leads to a blue sky**. Most colours in nature are caused by pigments = selective absorption - sky colour is different - there is nothing blue in the sky!



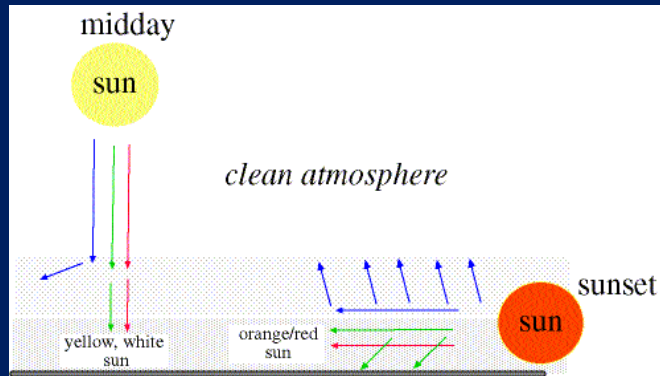
White Clouds

Droplets $\sim 50 \lambda$ - scatter all λ 's equally well, hence white clouds.
Water droplets are transparent - there is nothing white in clouds!



Red Sunsets

With a low sun its rays travel through such a long path length all blue light is scattered out leaving only redder wavelengths.







‘Black’ - Dark Clouds Either in the shadow of other clouds or self-shadowed or clouds thin - most light passes through and hence the cloud looks greyer. The thin edges of clouds when back lit are therefore brighter - the **silver lining**.



Smoke

Also looks buish if particles are fine enough. Whiter (greyer) if particles larger. For very large grains reflection dominates so looks the same colour as the particles, e.g. dust storm.



Twilight - The sky does not go immediately black as the sun drops below the horizon - The Twilight Arch.



Even after sunset the sky above the observer can still scatter blue light rays downwards - sky can therefore still be blue after sunset - eventually the sun will be low enough for all atmosphere to be in **shadow** (this effect is another demonstration that the earth is spherical!)

Civil twilight sun 6° below horizon

Nautical twilight sun 12° below horizon

Astronomical twilight sun 18° below horizon

Rays in the lower atmosphere are preferentially redder - these combined with blue light from above give **the purple light**

Looking away from the sun the observer can see the shadow of the earth projected into the sky - this will 'rise' as the sun gets lower. A pinkish band is seen above - the twilight wedge, anti-twilight arch or band of Venus.



Air Light

Most distant ridges - greater path-length through air - more scatterers
- more air-light reaches observer.

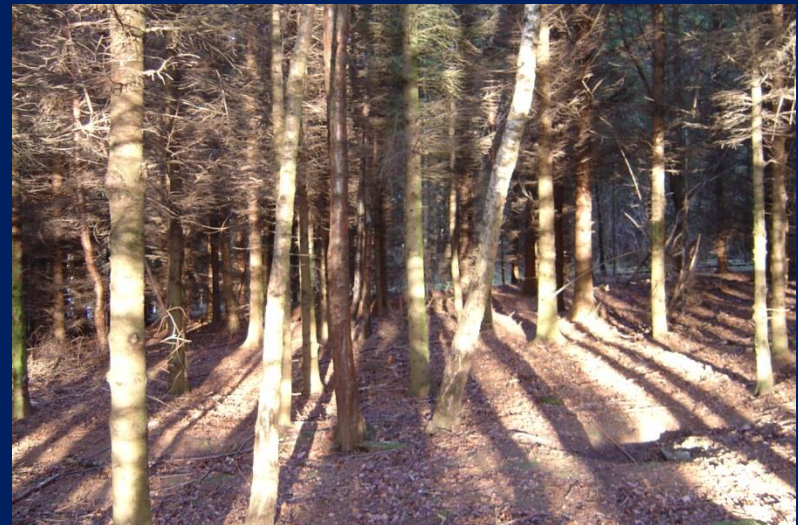


Crepuscular rays

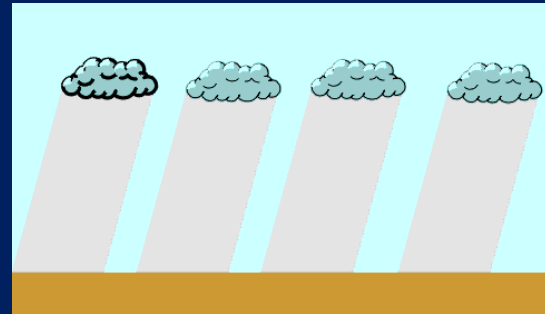


Perspective

Edges of buildings appear to converge to a vanishing point on the horizon (in 2D) - but they are really parallel lines (in 3D).











Anti-crepuscular rays



How many
phenomena can
you identify here?



Contrail shadows



Angular variation of scattered light intensity

(A) Small Particles



Size: Smaller Than $\frac{1}{10}$ the Wavelength of Light
Description: Symmetric

(B) Large Particles

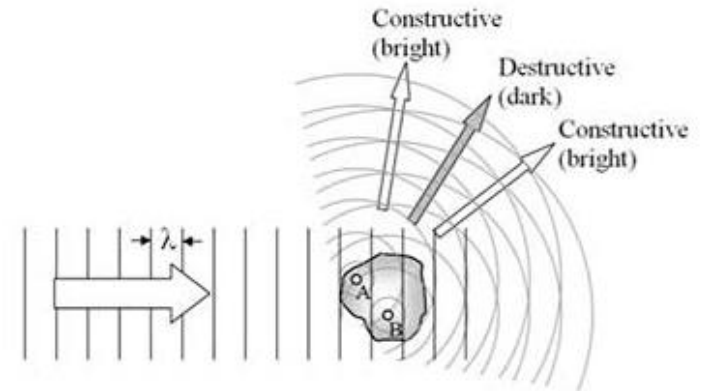


Size: Approximately $\frac{1}{4}$ the Wavelength of Light
Description: Scattering Concentrated in Forward Direction

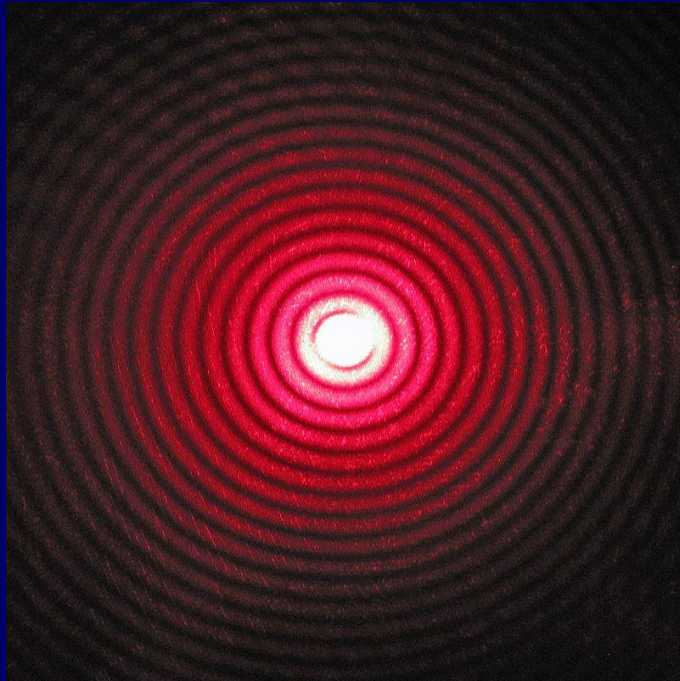
(C) Larger Particles



Size: Larger Than the Wavelength of Light
Description: Extreme Concentration of Scattering in Forward Direction; Development of Maxima and Minima of Scattering Intensity at Wider Angles



Colours of the Corona



Diffraction pattern of small obstacle in red light. For blue light the pattern would be similar but smaller in angle. When superimposed the overlap of different colours produces white at the centre with red on outer edge. Outer circles have differing areas of overlap hence different mixtures of colours.

As with other optical phenomena, in a sky full of particles the pattern of light we see is a large scale copy of the pattern produced by an individual particle.

Effects caused by the diffraction of light



A Lunar corona

Solar Corona



Cloud iridescence



Also Nacreous Clouds - at 20 - 30km.



The Brokenspectre

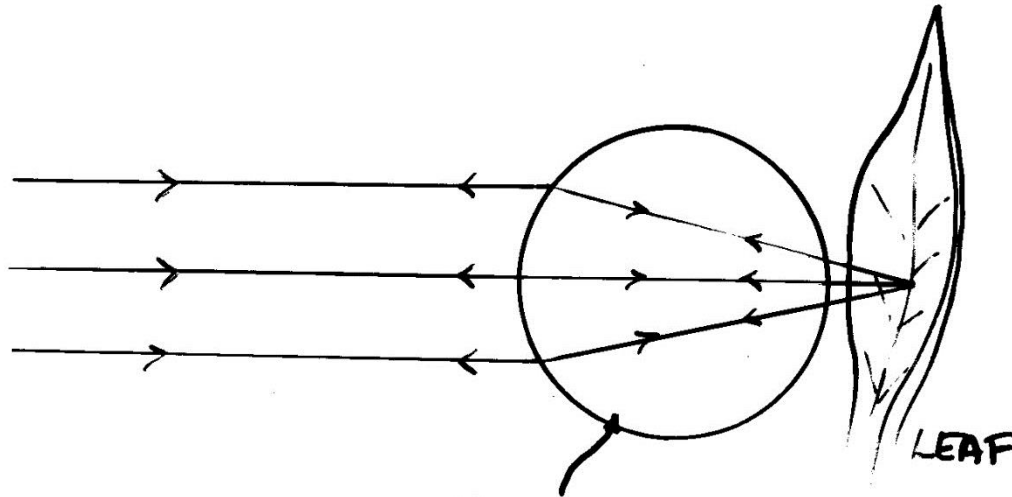








HEILIGENSCHN



Spherical droplet focuses light at a point just behind - this can get reflected back into the drop and returned preferentially back the way it came from i.e. the sun! To see the returning rays we therefore look to the anti-solar point (shadow of head). A similar effect is utilised in 'cats-eyes' and glass beads on road signs.







Twinkling of Stars

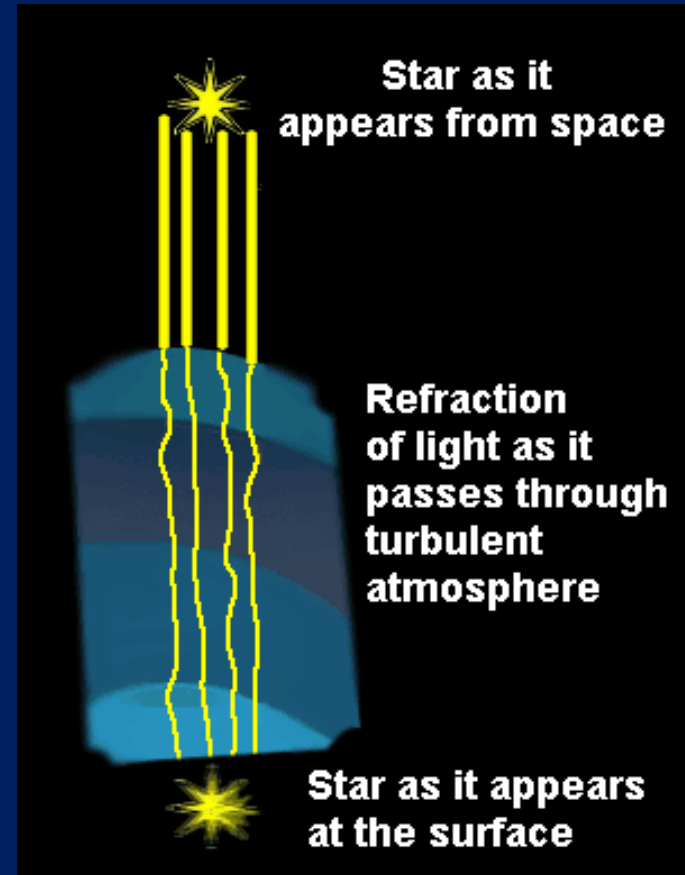
Mainly a refraction effect.

Pockets of turbulent air will be of slightly different densities and hence refractive indices - each pocket boundary will bend light slightly.

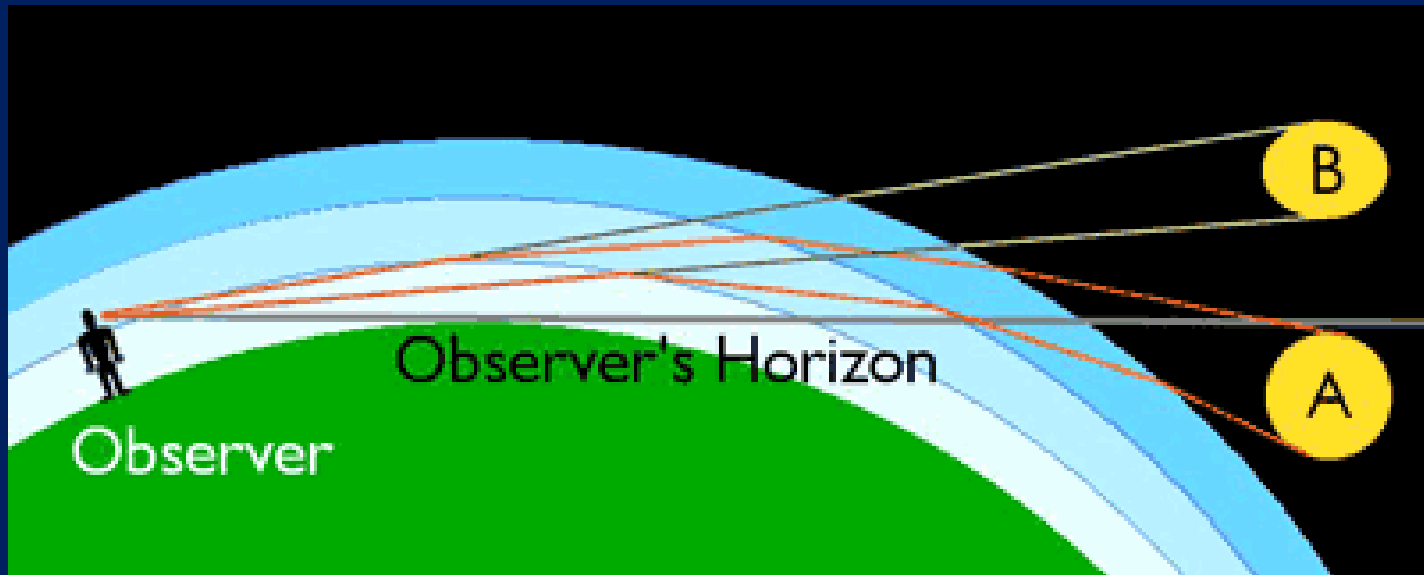
Some rays diverge away from the observer - the star fades - some rays may be diverted towards the observer - the star brightens. This happens on very small timescales - hence twinkling.

Starlight passes through hundreds of 'cells' - the image is constantly moving and varying in brightness. Also a prismatic effect will cause colour changes.

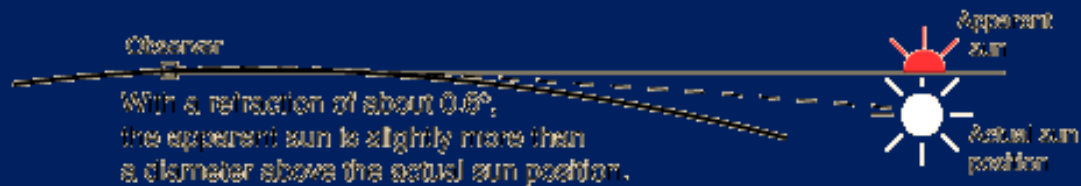
Because of their relatively large angular size - **planets twinkle less than stars.**



Atmospheric Refraction



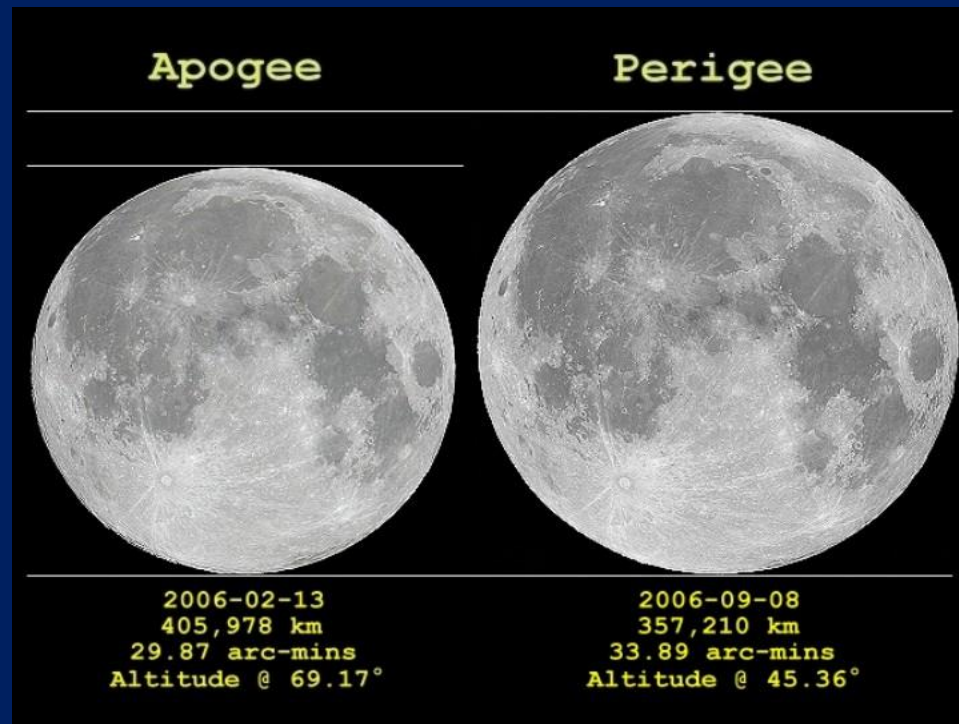
Note that the sun at B is slightly 'squashed' – the top is lifted less than the bottom.



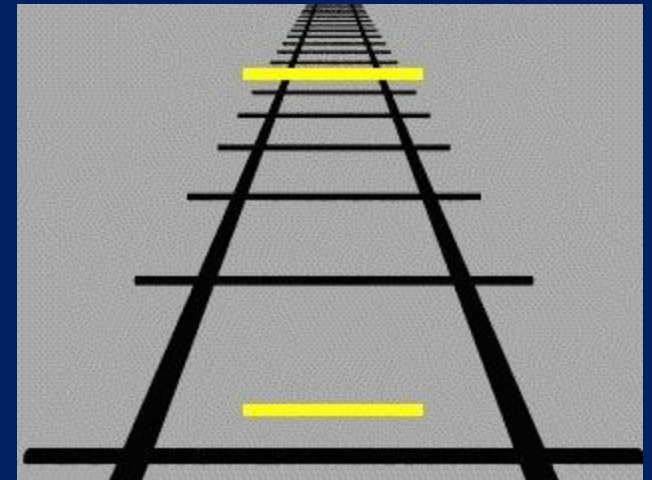
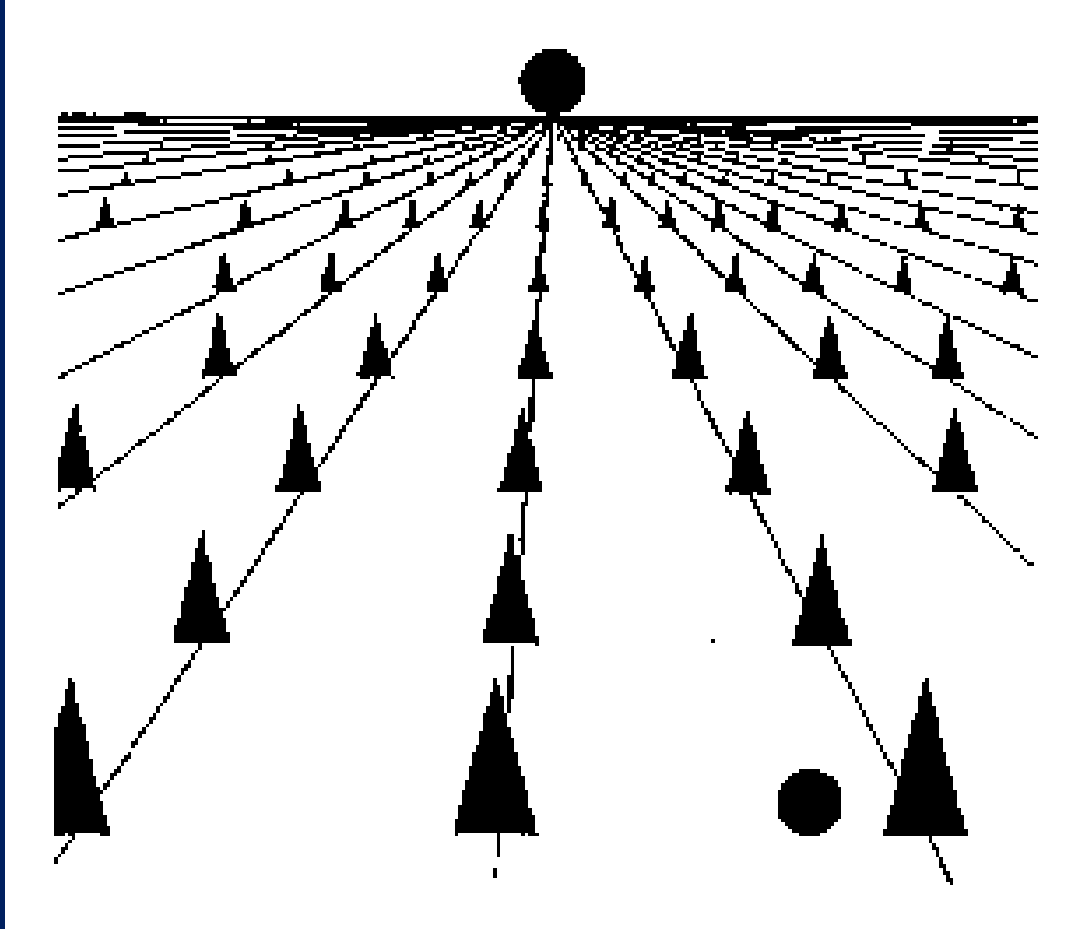


This effect does not explain **the moon illusion** which is mainly psychological – as the Moon gets higher in the sky it seems to shrink in size.

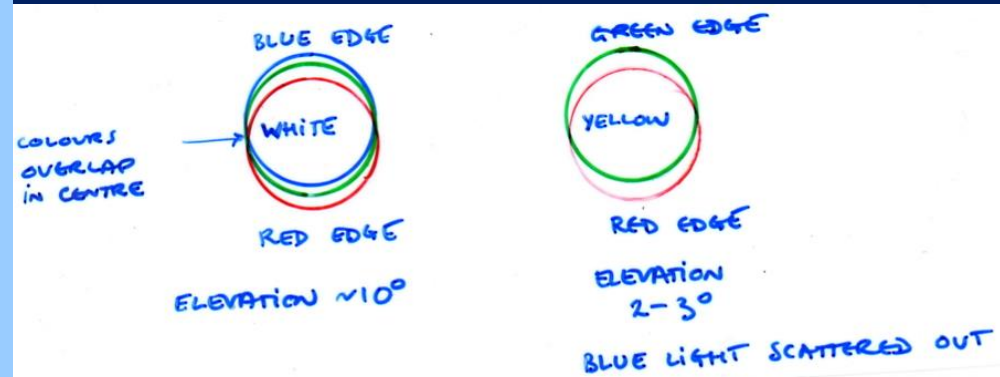
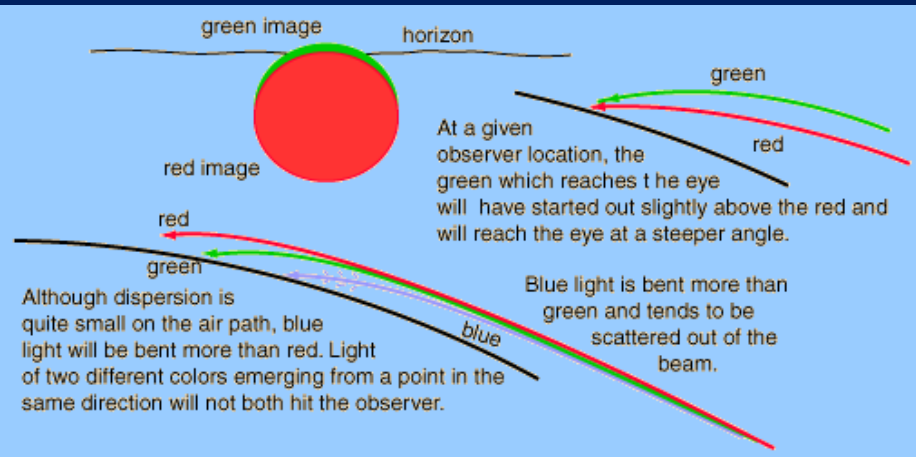
The distance to the Moon varies by about 10% which changes its apparent size by the same amount – however this couldn't happen on the same night!



Optical illusions that may be related to the Moon illusion.



The Green Flash

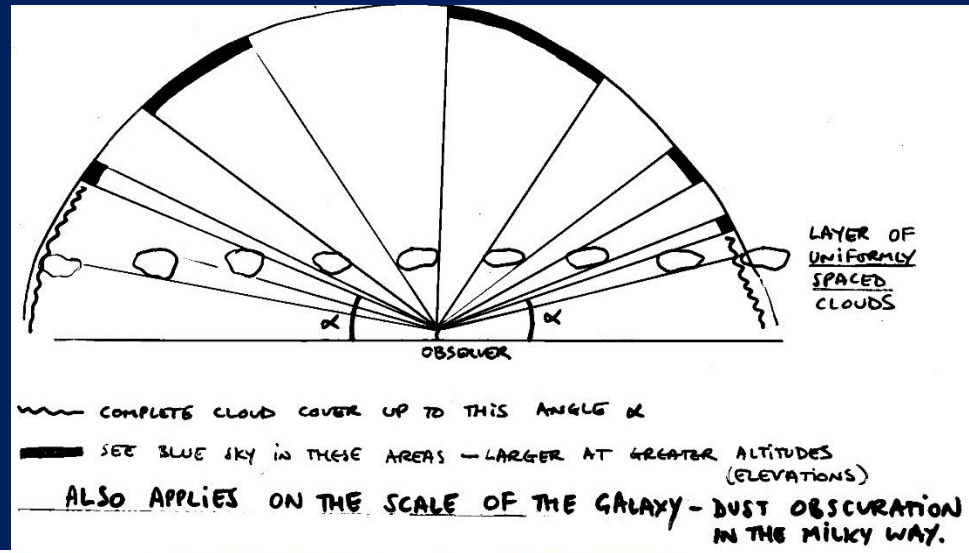






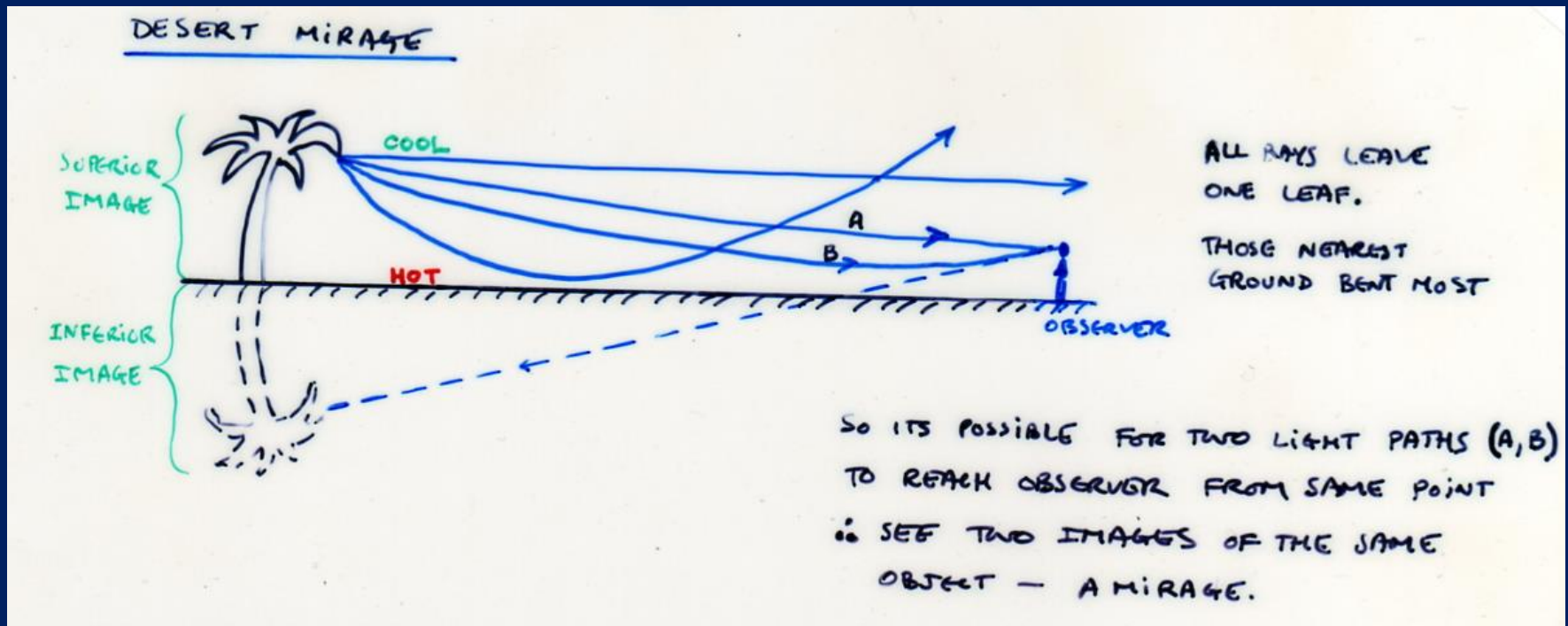


Cloud blocking



Mirages

If the ground is hot the air just above is also hotter and less dense than air above - light rays therefore bend up into cooler air.



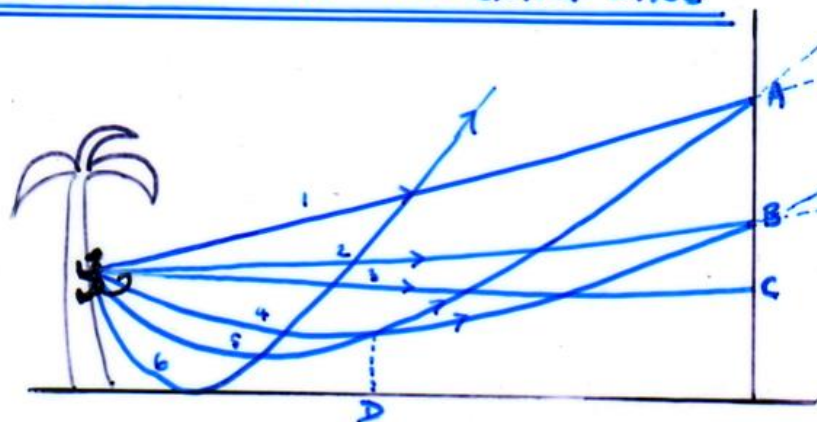
The inverted image looks like reflection in water - even though there is no reflection and no water involved!

The classic mirage



ORIGIN OF THE VANISHING LINE

42b



SIX RAYS FROM ONE POINT ON MONKEY. FROM 1-6 EFFECT OF REFRACTION GREATER

- NONE ARRIVE TO POINTS LOWER THAN C.

IF OBSERVERS EYE BELOW THAT POINT TAKEN THEY WOULD NOT BE ABLE TO SEE THAT POINT ON THE MONKEY.

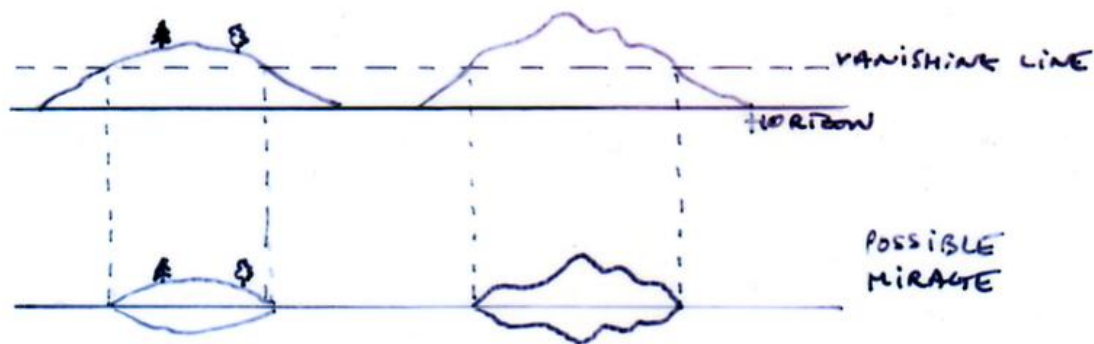
POINT C \therefore LIMITING CASE.

FROM THERE WOULD SEE:



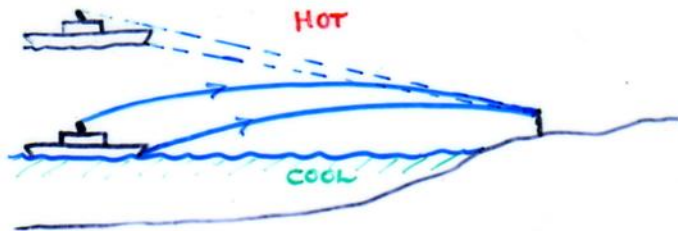
CLOSER TO THE OBJECT VANISHING LINE LOWER ON TREE E.G AT POINT D OBSERVER COULD BE EVEN LOWER THAN POINT C BUT RAYS 4 & 5 REACH THAT PLACE.

FARTHER AWAY VANISHING LINE HIGHER.



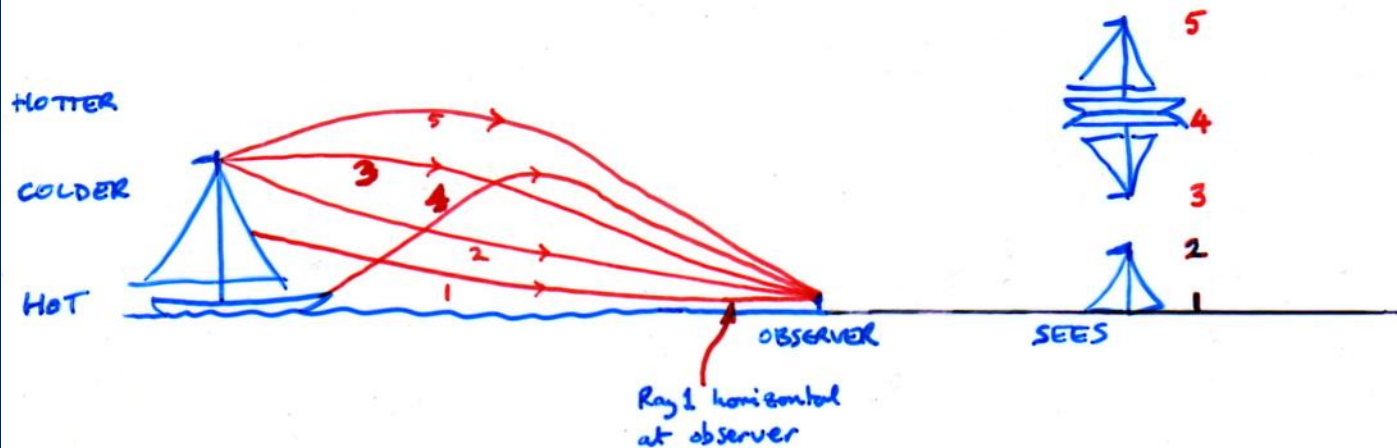
SUPERIOR MIRAGES

BY INVERTING TEMPERATURE GRADIENT



DEPENDENT ON THE ANGLE THAT THE RAYS MEET THE EYE THE IMAGE CAN BE MORE OR LESS DISTORTED OR STRETCHED.

MORE COMPLEX MIRAGES FORM IF TEMP. GRADIENT MORE COMPLEX



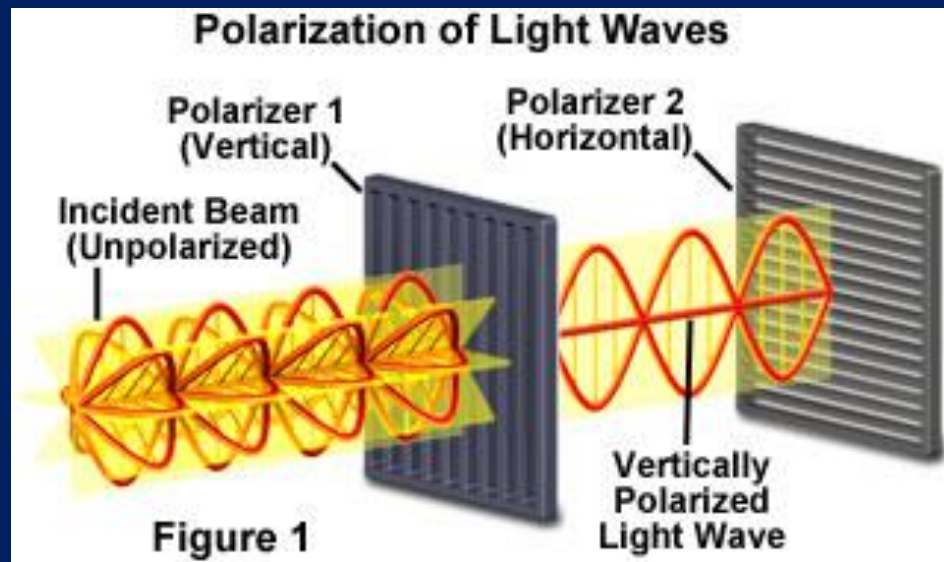
THERE ARE THREE LIGHT PATHS FROM THE FLAG THAT CAN ARRIVE AT OBSERVER FROM DIFFERENT DIRECTIONS \therefore SEE IT AT THREE DIFFERENT HEIGHTS, 2, 3 & 5.

Superior Mirages



Polarisation

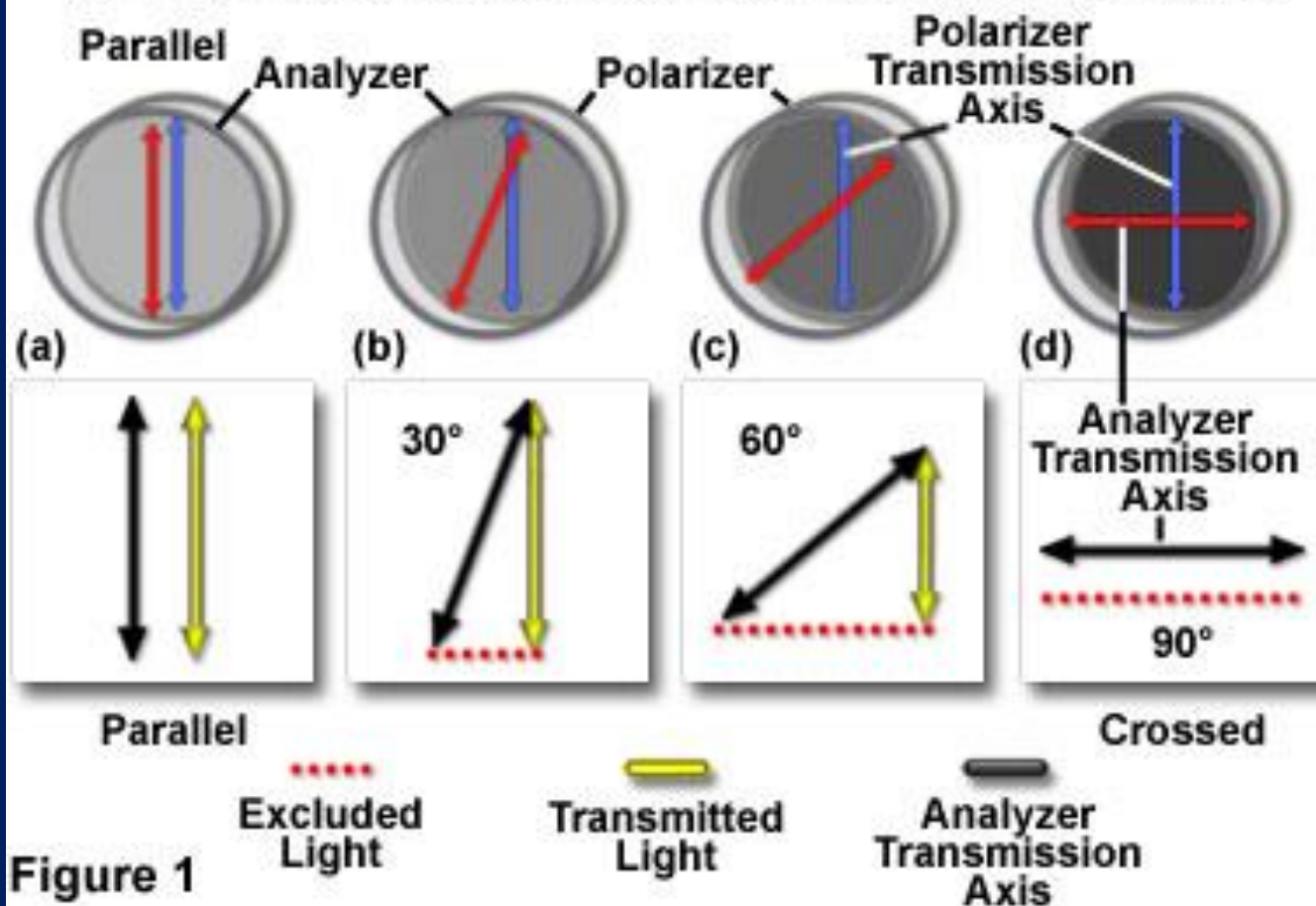
Electro-magnetic theory of light - light is comprised of varying electric and magnetic fields travelling at 300,000km/s as a transverse wave motion (like those in a shaken rope). Vibrations occur in planes perpendicular the direction of travel.



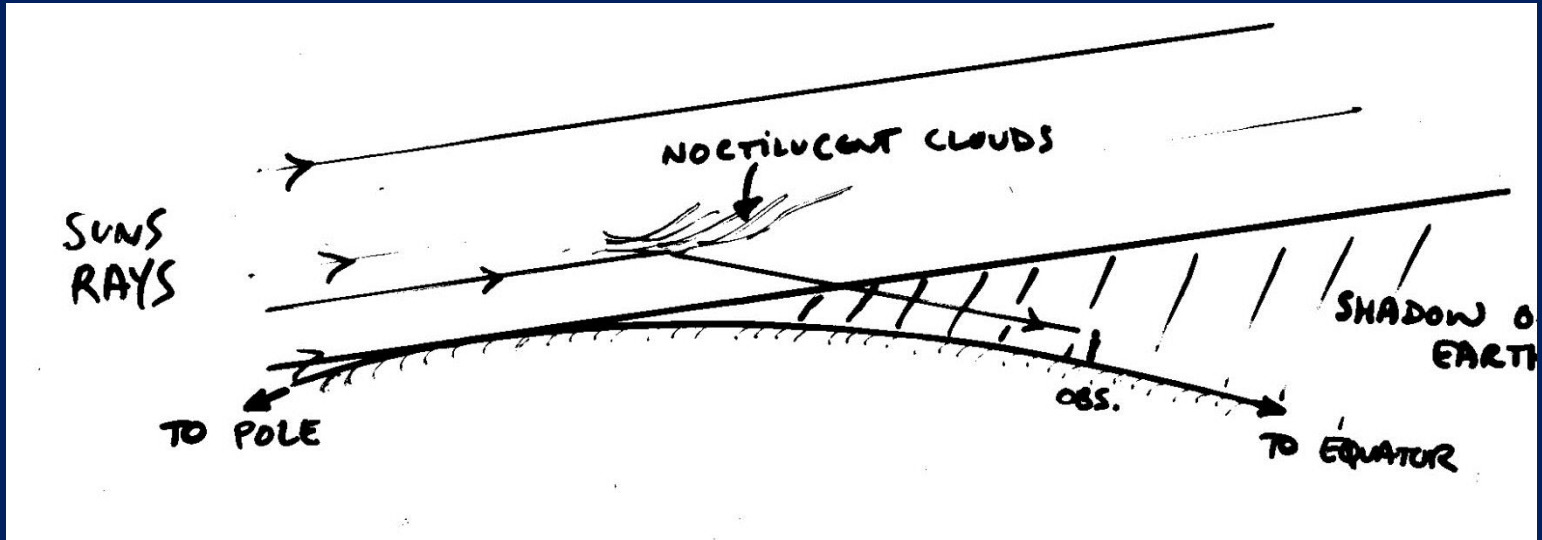
Polarising sunglasses work in an analogous way. The molecular structure of the material selectively absorbs and scatters light of different polarisations.

Light is also polarised by reflection.

Transmission of Polarized Light Through an Analyzer



Noctilucent clouds



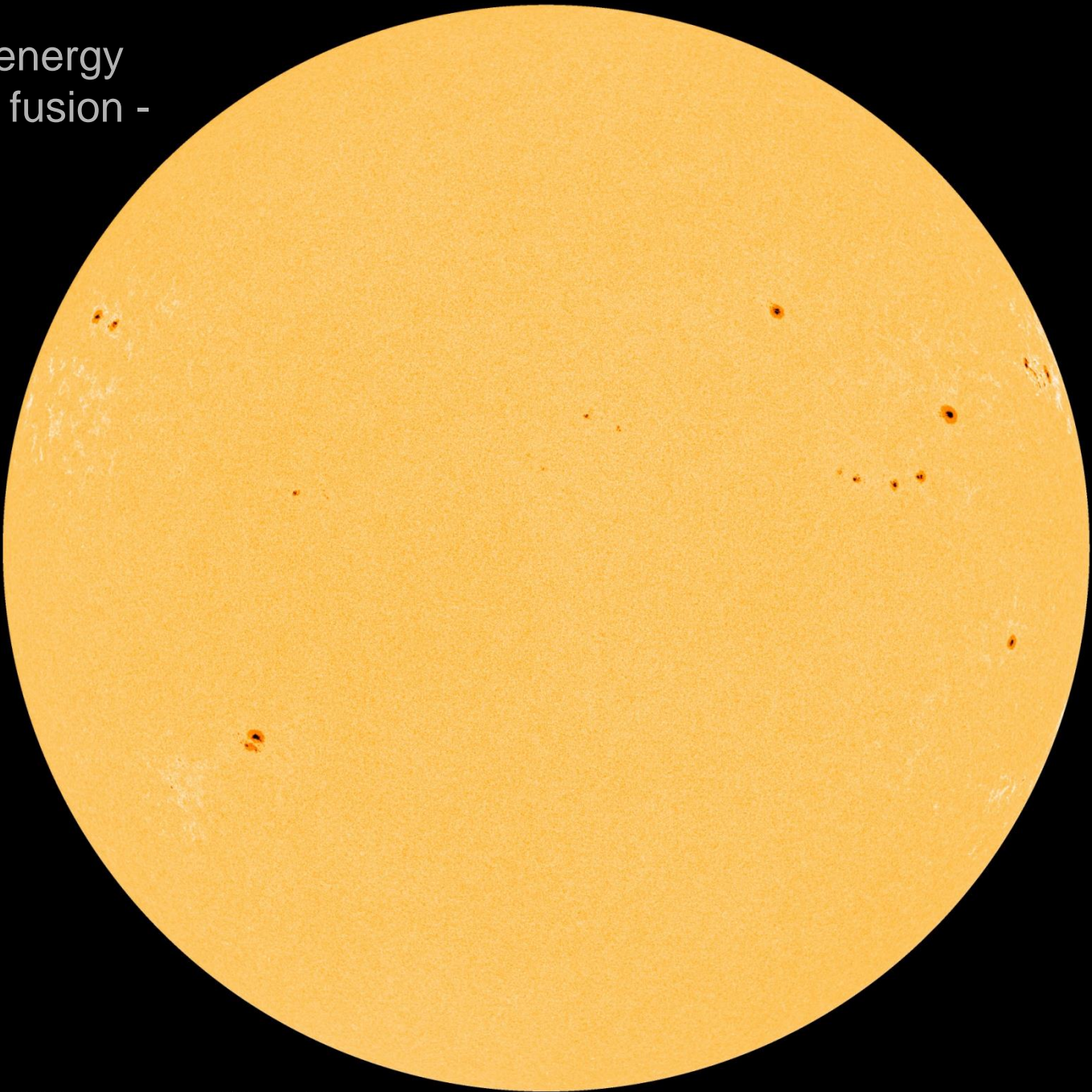
Clouds at altitudes of 80 - 85km can be visible even at mid-night at high latitudes in the summer months. They are very faint and not visible in the bright daytime sky.



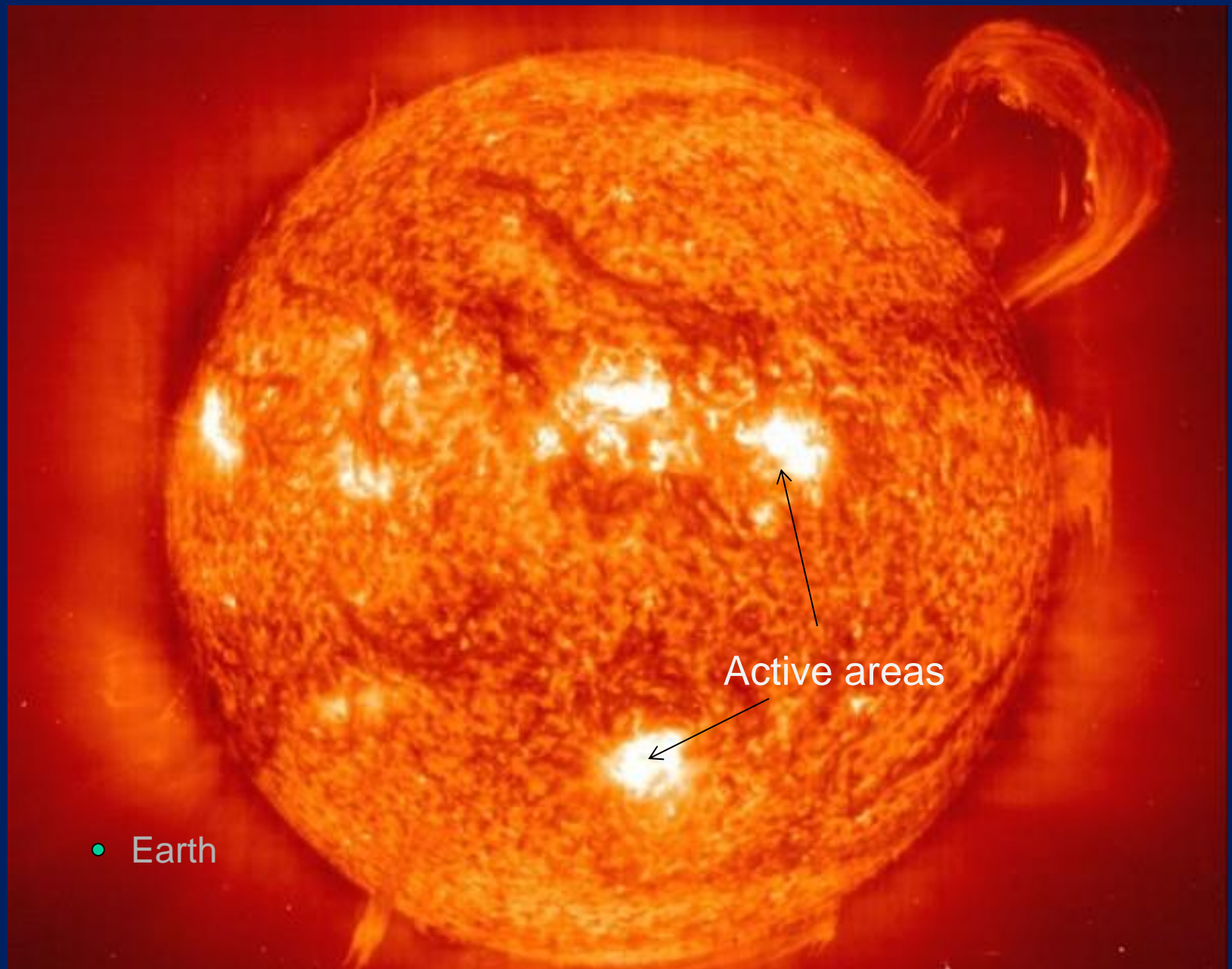




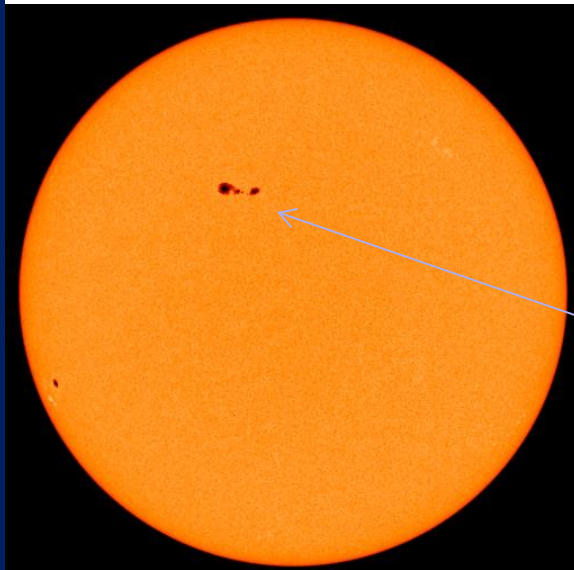
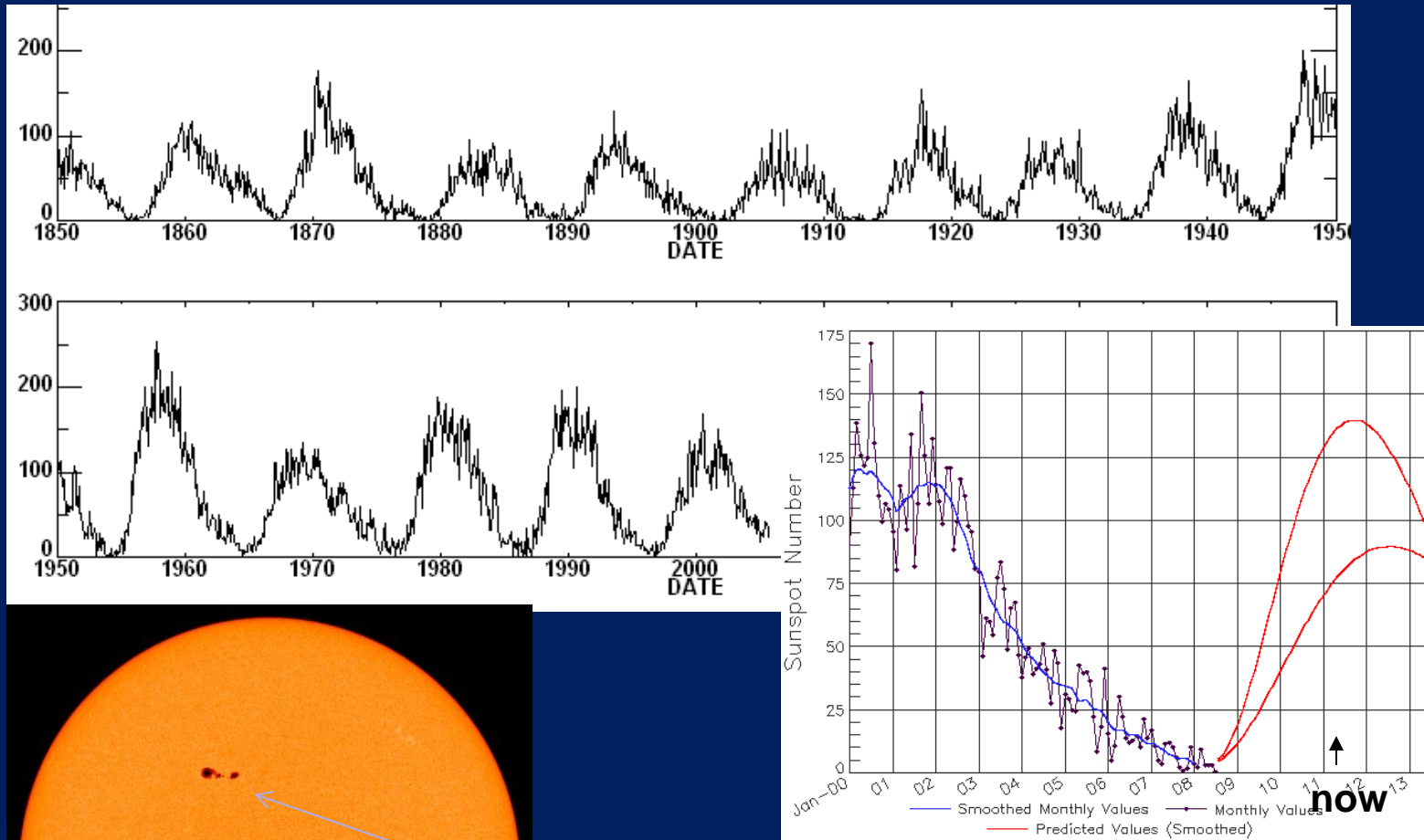
The Sun -
generates energy
via nuclear fusion -
it is *a star*



The Sun as seen through a H α telescope

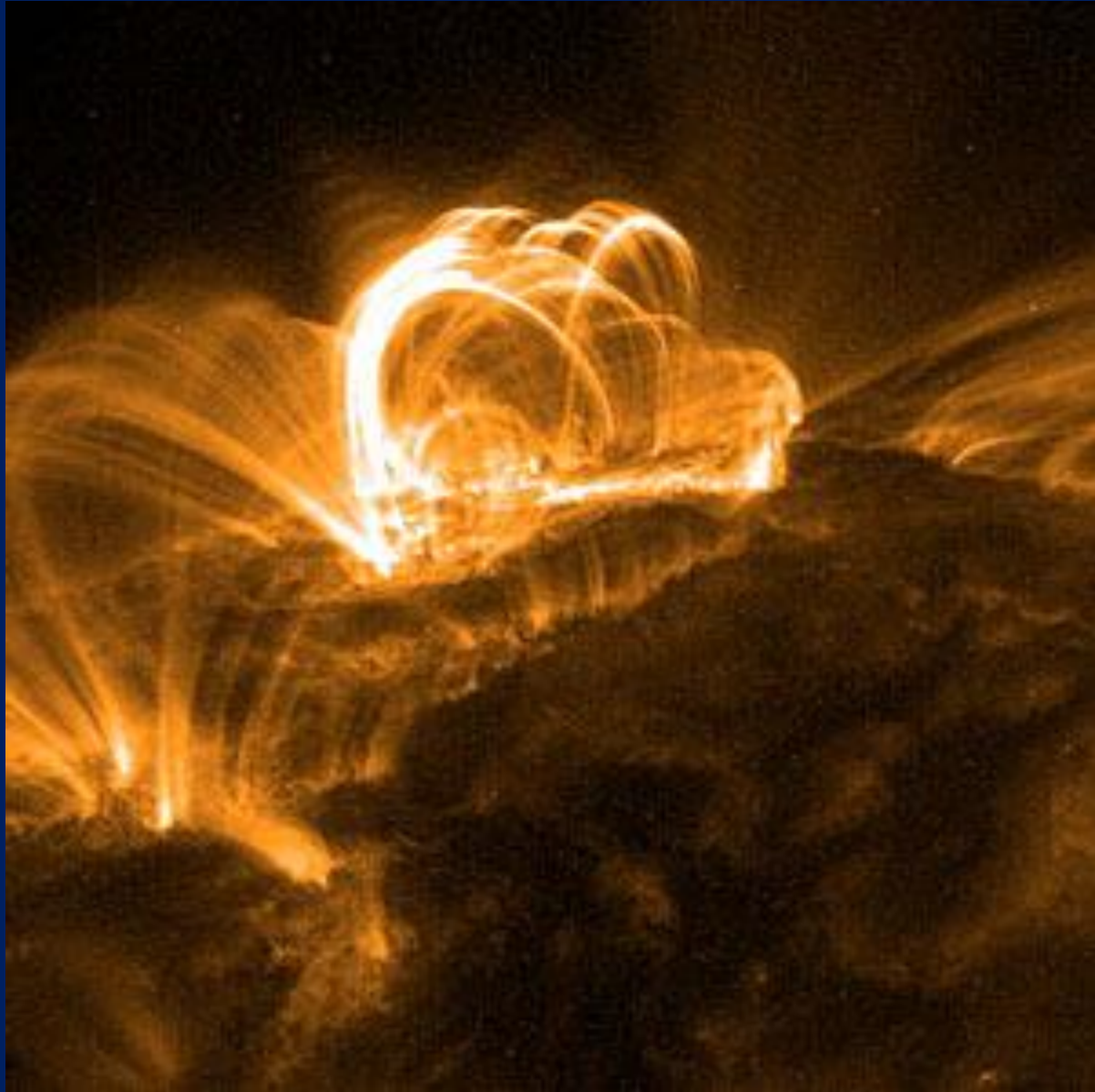


The 11 year cycle of solar activity – finally seems to have got going after the most prolonged minimum for 100 years.

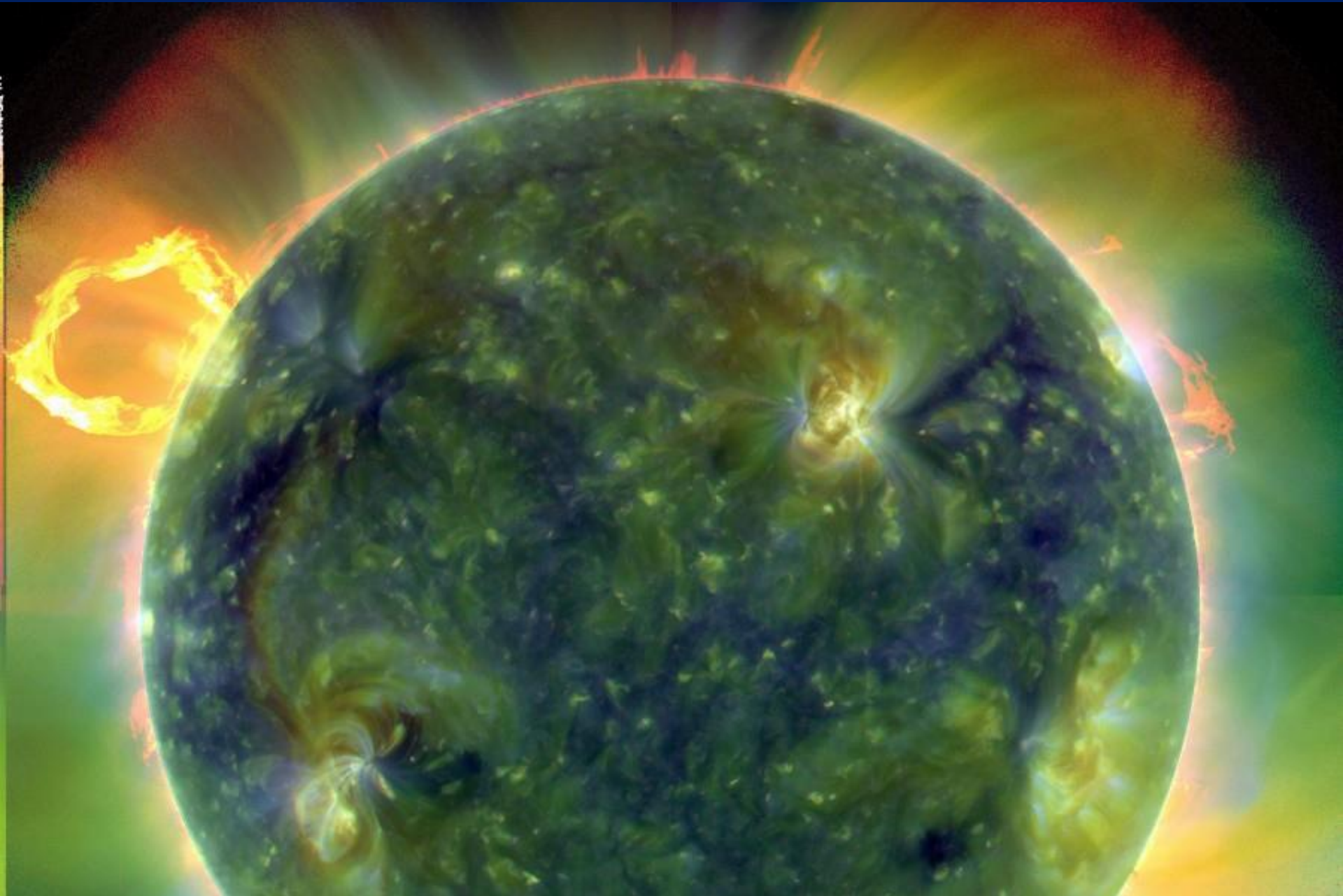


sunspots

Solar flare

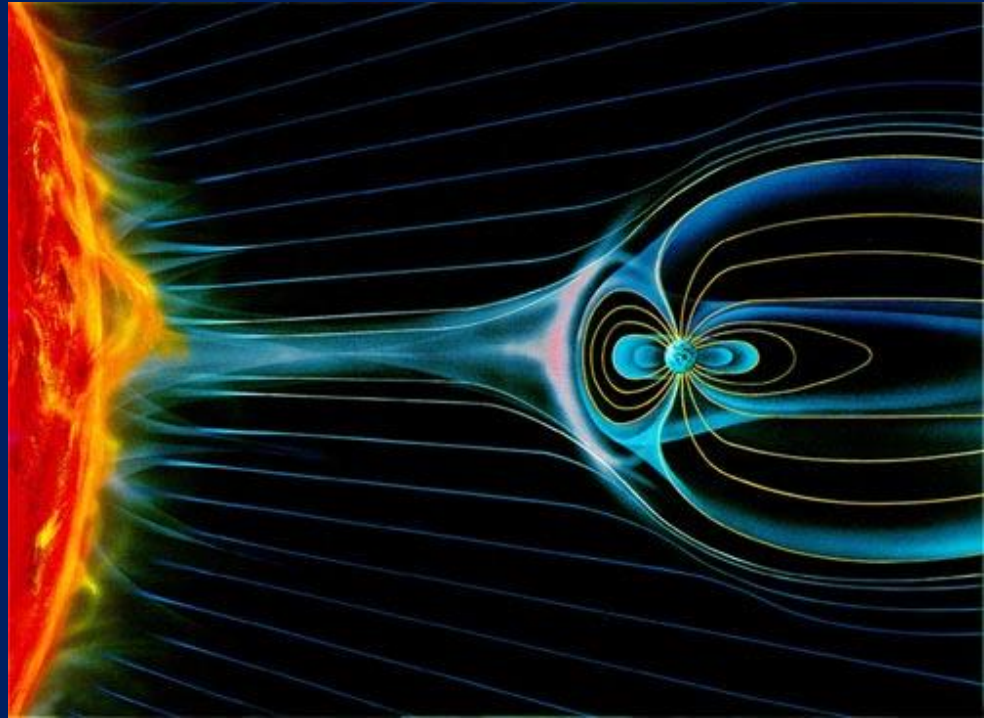


Solar Dynamics Observatory – the sun at extreme UV wavelengths

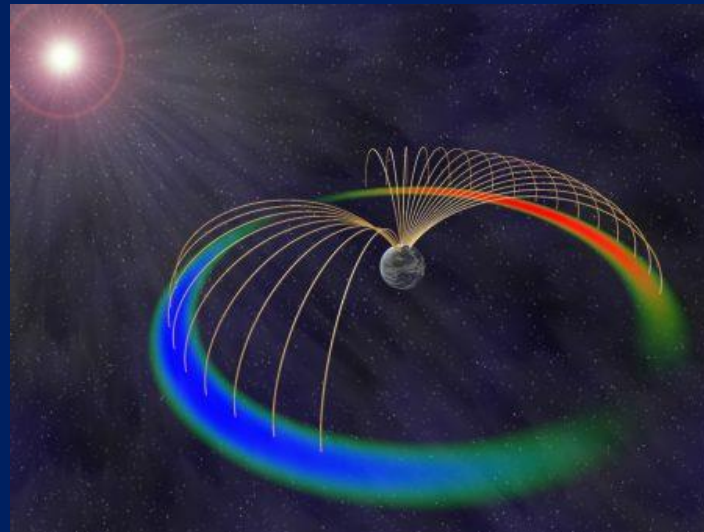


The Aurora Borealis (and Australis)

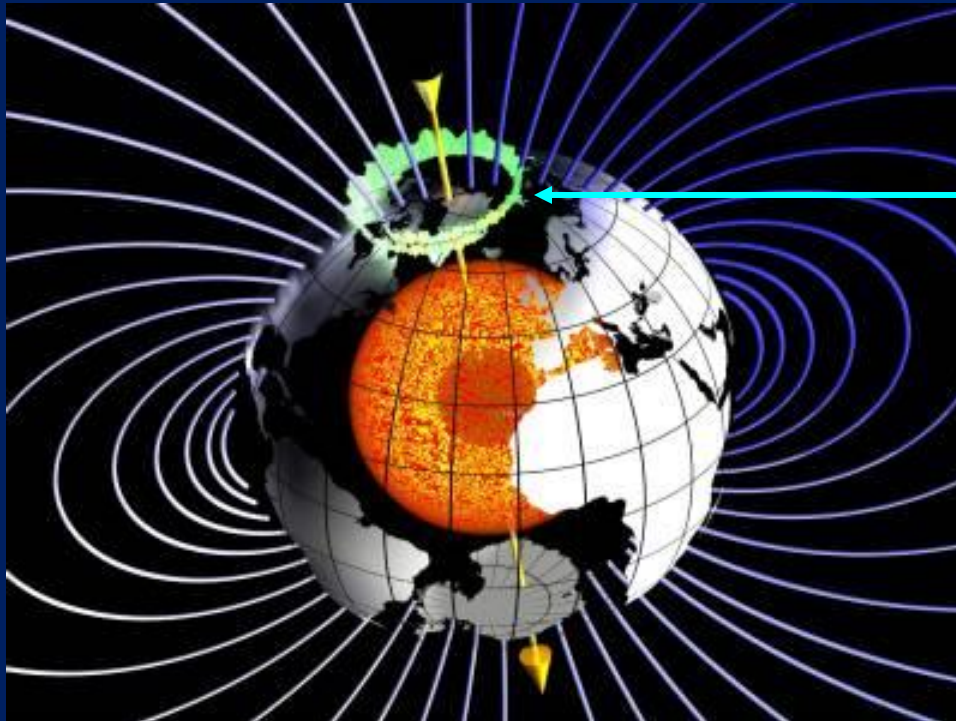
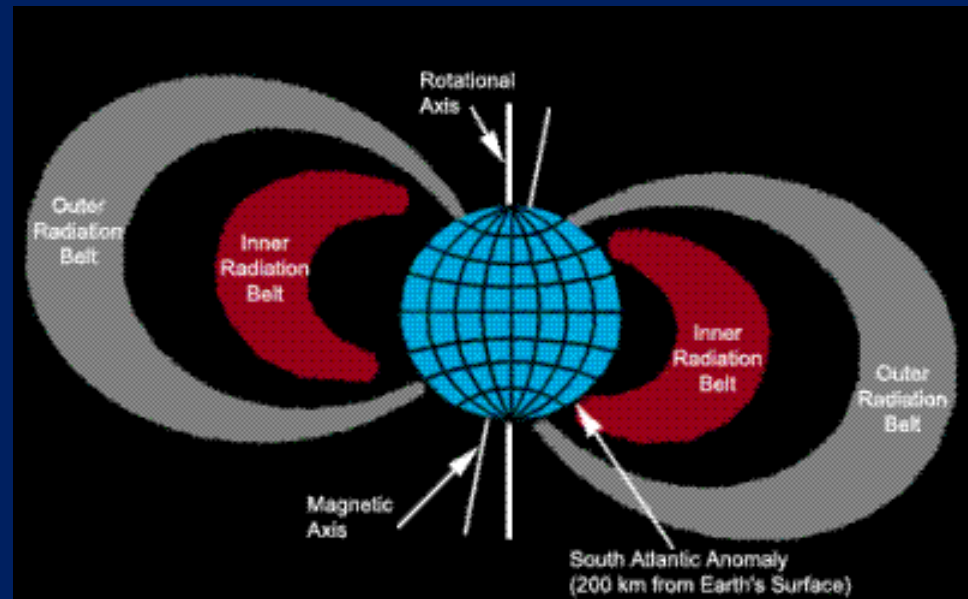
Formed by the interaction of the solar wind and the Earth's magnetic field



Charged particles flow along the lines of magnetic force



The magnetic field of the Earth



The aurora are produced in a circle centred on the magnetic poles of the Earth.



Green = oxygen, which can also produce red higher up if high energy. Nitrogen = faint blue and produces crimson colour in lower atmosphere.











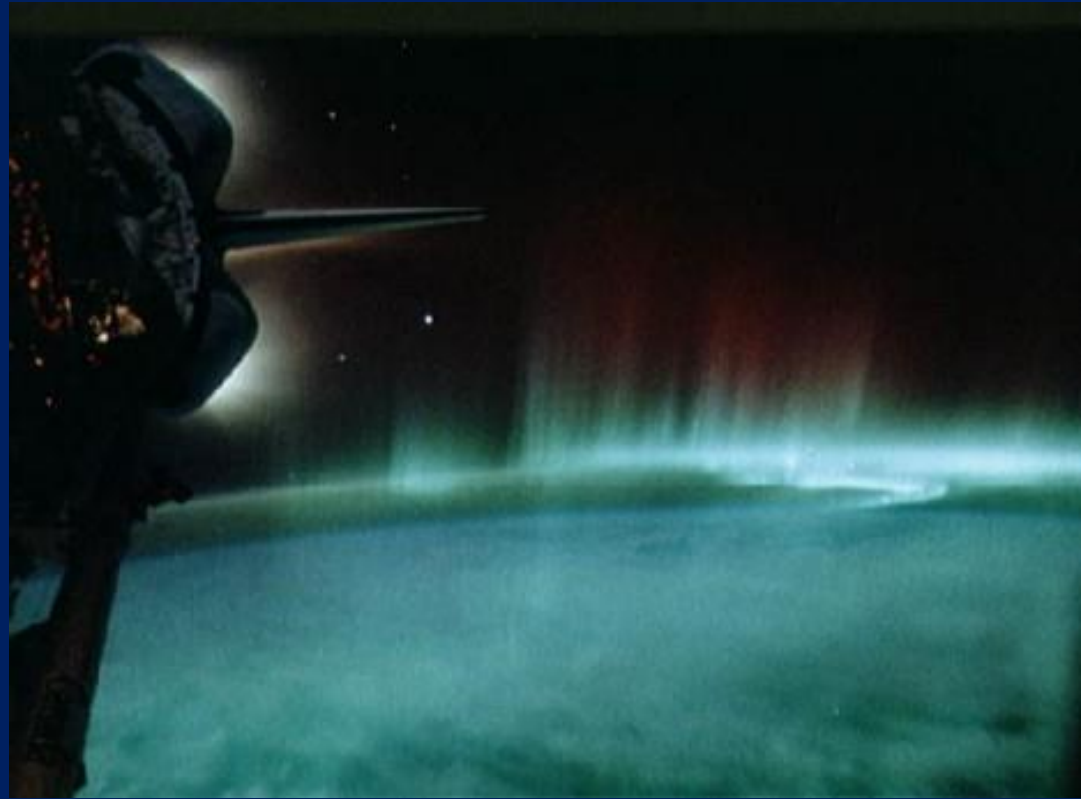




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Aurora seen from orbit

Space shuttle



ISS













Leonid meteor shower – Nov 16-17, from comet Temple-Tuttle