

WS7: THERE IS MORE TO ASTRONOMY THAN MEETS THE EYE!

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Abstract

In 1800, William Herschel discovered infrared light in the Sun's spectrum. This was the beginning of a two hundred year journey of discovery. Since then we have been able to detect signals from space in all parts of the electromagnetic spectrum.

This workshop will provide a worksheet for each band of the spectrum covering:

- the wavelengths and energies involved
- the telescopes used in detection
- the significance of the astronomy and
- how to relate the energy band to everyday items.

Updated October 2013

INTRODUCTION

Astronomy started when early man recognised the Sun, Moon and the stars. Once established in visible light, observational developments continued:

- 1800 – William Herschel discovered infrared in the Sun's spectrum
- 1856 – Charles Piazzi Smyth detected infrared in the light of the Moon
- 1933 – Karl Jansky detected radio emission from the Sun and the Milky Way
- 1937 – Grote Reber built the first Radio Telescope
- 1950s – Rockets lifted UV and X-ray detectors above the atmosphere
- 1969 – Vela-5 Gamma-ray satellite launched
- 1970 – Uhuru X-ray satellite launched
- 1978 – International Ultraviolet Explorer satellite launched.

Since then many observatories have continued the work both on Earth and in space.

This workshop will attempt to illuminate each of these bands of radiation and give an example of everyday use that can be shown in the classroom.

Our view of the Universe is severely limited by our eyes and by the Earth's atmosphere. Our eyes only detect a tiny part of the electromagnetic spectrum – the visible region. The Earth's atmosphere absorbs many other regions of the spectrum.

The illustration below shows the visible and radio observations can be made from the surface of the Earth but gamma ray, X-ray, ultraviolet and infrared observations have to be made from space.

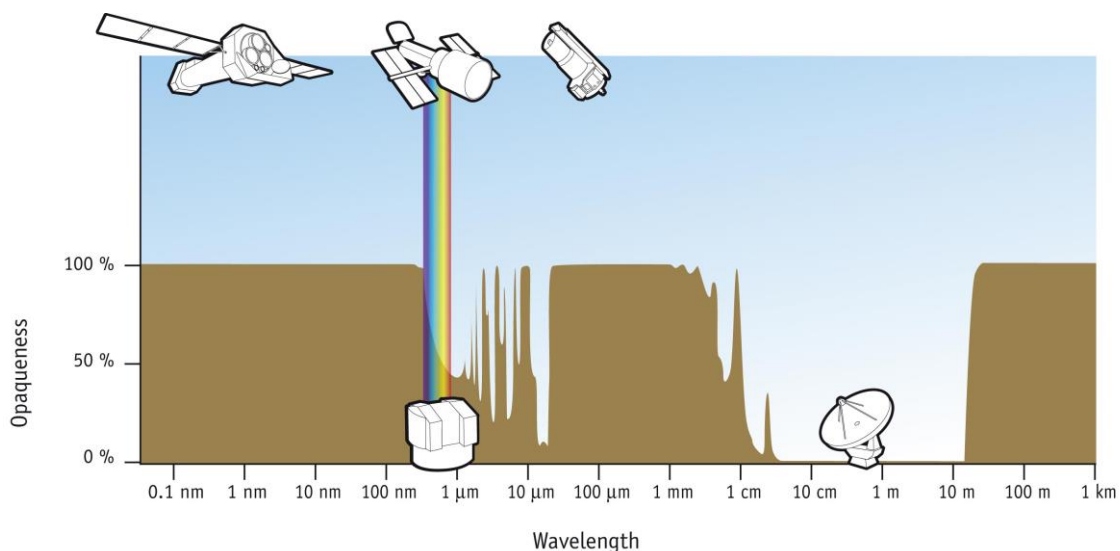


Figure 1: Absorption of electromagnetic waves by the Earth's atmosphere. F. Granato (ESA/Hubble)

RADIO – METRE WAVELENGTH

Radio waves are created when:

- Charges are accelerated or
- Electrons change energy level in an atom.

Accelerated charges create “radio noise” whereas atomic energy changes create “spectral lines”. Both indicate the amount of material in a gas cloud or galaxy. However a spectral line allows speed to be measured by the Doppler Shift. The earliest and most common is that of neutral hydrogen atoms. When a hydrogen atom forms from a free proton and electron they can bond with their spins parallel or anti-parallel. The parallel state has the slightly higher energy and eventually the spins will flip to become anti-parallel.

Calculation: Emission from Neutral Hydrogen spin flip – wavelength 21 cm.

Energy of Photon = Planck’s Constant $\times$ Speed of Light / Wavelength

Substituting: Energy = $6.63 \times 10^{-34} \times 3.0 \times 10^8 / 0.21 = 9.47 \times 10^{-25} \text{ J}$ ($5.9 \mu\text{eV}$)

Multiple of Visible Wavelength: 420 000

To make a mirror for any electromagnetic wave the surface must be smooth to at least one twentieth (0.05) of the wavelength to be reflected.

Large radio telescopes like the Lovell Telescope at Jodrell Bank near Manchester (**United**) can only work down to a few centimetres wavelength. They do not have a good enough surface to reflect shorter wavelengths.

However the large collecting area is very useful for detecting faint signals:

- Pulsar discovery and monitoring
- Measurement of spectral lines to determine:
 - the speeds of gas and dust clouds and galaxies
 - the rotation rate of galaxies in the search for Dark Matter.

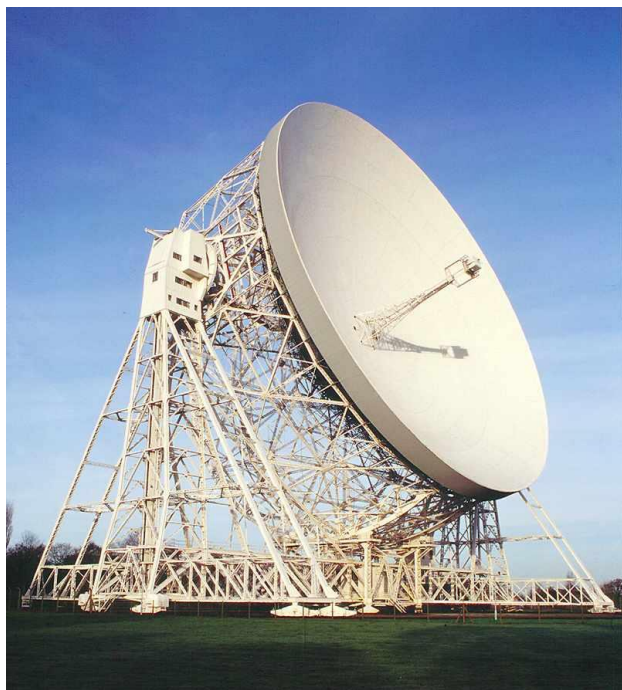


Figure 2: The Lovell Telescope (JBO)
www.jb.man.ac.uk/

In the 1950s, Jan Hendrik Oort confirmed the shape of our Galaxy using radio telescopes in Holland. Light cannot penetrate the gas and dust of our Galaxy. However, radio signals can be detected from the distant spiral arms.

More recently it has been accepted that all galaxies have a super-massive black hole at their centre.

This image of 3C31, a dusty elliptical galaxy, shows evidence of the super-massive black hole at its centre. Gas, dust and stars are falling into the black hole. Some material does not reach the event horizon and is spun out in jets. The plasma in these jets is moving at close to the speed of light. When it collides with the surrounding gas and dust it emits electromagnetic energy. The composite image shows the radio and visible energy. In the visible image the jets are very faint but in the radio they are seen to extend very far from the galaxy.

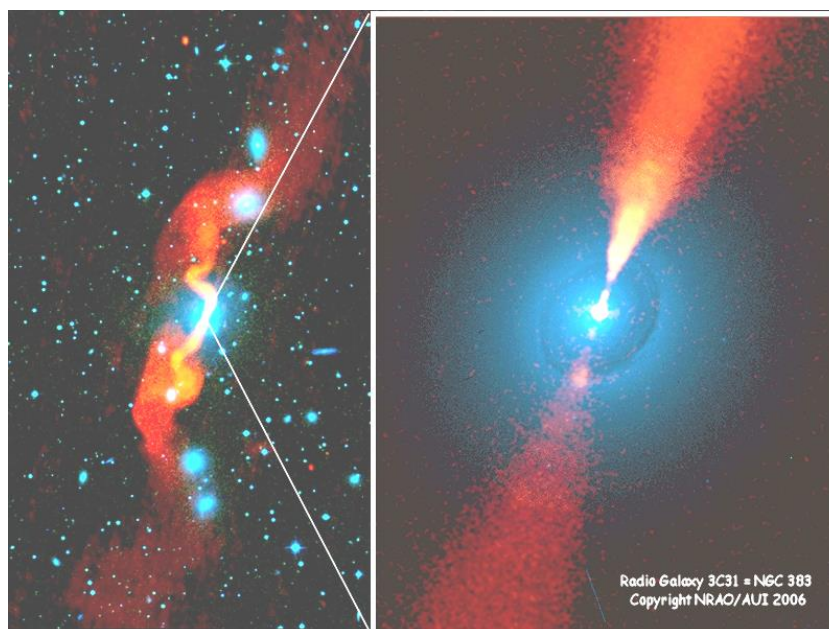


Figure 3: Radio (Red) and Optical (Blue) images of the galaxy 3C21.
Left: VLA 21 cm radio image and a Palomar Sky Survey blue image
Right: VLA 3.6 cm radio image and a Hubble Space Telescope WFPC2 image.

You can also hear some radio astronomy signals. Go to:
www.jodrellbank.manchester.ac.uk/multimedia/audio for the sounds of pulsars.

Calculation: Your Mobile Phone – How long is your mobile phone? An efficient aerial cannot be shorter than a quarter of the wavelength it is operating on. Please measure your phone!! Confirm the statement above by multiplying the length of your phone by 4 to find the wavelength in use. Then divide by the speed of light. This should give about 900 MHz for GSM phones.

VHF Radio Demonstration: Tune to an unused part of the band. A small percentage of the noise you hear comes from the Cosmic Microwave Background Radiation. Note that the ionosphere stops Short Wave radio noise from reaching the surface of the Earth.

RADIO – MILLIMETRE WAVELENGTH

Millimetre wavelength radio waves are created when very cold molecules:

- Change rotational state
- Change vibrational state or
- Emit blackbody radiation.

Tiny electron energy changes also create millimetre wavelength radio waves.

In a very cold gas cloud, perhaps at a temperature of 30 K, molecules can change from one quantised rotational state to another. The energy difference between these states is very small hence a microwave photon is emitted or absorbed.

Calculation: Emission from cold rotating Carbon Monoxide changing from rotational state $J = 3$ to state $J = 2$ – wavelength 0.867 mm.

Energy of Photon = Planck's Constant $\times$ Speed of Light / Wavelength

Substituting: Energy = $6.63 \times 10^{-34} \times 3.0 \times 10^8 / 0.867 \times 10^{-3} = 2.29 \times 10^{-22} \text{ J (1.4 meV)}$

Multiple of Visible Wavelength: 1 740

To make a mirror for any electromagnetic wave the surface must be smooth to at least one twentieth (0.05) of the wavelength to be reflected.

The Atacama Desert in Chile is the location of the ALMA (Atacama Large Millimetre Array) array. At an altitude of 5000 metres it is one of the driest places on the planet. There are fifty four 12 metre diameter and twelve 7 metre diameter radio telescopes on site. These telescopes are small enough to have surfaces accurate to 0.025mm. This allows millimetre wavelengths to be received efficiently. The signals are digitised and sent by fibre optic cables to a powerful computer system that multiplies them in a special way. By recording the data as the Earth turns, maps of the radio sources are produced. These maps also contain information about the spectral lines present.

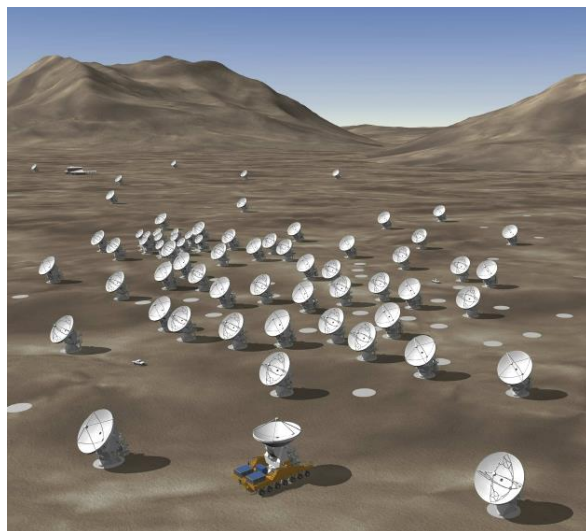


Figure 4: The ALMA Telescope Array (ALMA)
www.almaobservatory.org

The large collecting area and very dry site will allow the telescope to:

- directly image exo-planets, possibly discovering traces of life
- detect molecules in clouds of gas and dust and
- detect faint signals from the very first stars and galaxies.

In the optical, dust obscures star-forming activity in the Horsehead Nebula. In the infrared, the hot, thin layer of dust around the cloud glows. At radio wavelengths, both dust and molecules glow, providing a wealth of information about the internal structure, density and kinematics of optically invisible regions. ALMA will map the glowing emission (the two rightmost panels) at the resolution of the optical image. (ALMA Observatory)

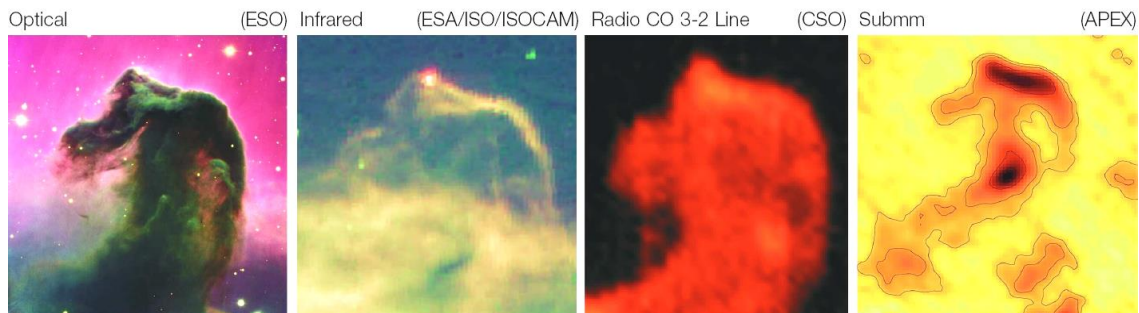


Figure 5: Comparison of Optical, Infrared, Radio and Sub millimetre images

From space, the Planck spacecraft will have an uninterrupted view of the microwave background. The microwave background is very uniform. However, for gravity to have had time to form the Universe we see today, there must have been slight unevennesses at the time the background was released – about 300 000 years after the Big Bang. Planck will study these variations in great detail.



Figure 6: The Planck Spacecraft. (ESA)

The Planck spacecraft has observed the cosmic microwave background radiation (CMB). Since the Big Bang, what once was a searing fireball has cooled to become a background sea of microwaves at 2.7 K. Planck is sensitive to temperature variations of a few millionths of a degree and has mapped the full sky over nine frequency bands from 30 to 857 GHz. The telescope has an aperture of 1.5m. The spacecraft is equipped with the means of cooling the detectors to temperatures close to absolute zero.

www.esa.int

Example: A domestic satellite dish receives at a wavelength of 100 mm.

INFRARED

Infrared waves are created when atoms and molecules:

- Change rotational state
- Change vibrational state or
- Emit blackbody radiation.

Very small electron energy changes also create infrared radiation.

Warm gas clouds and the surfaces of planets emit a continuum of blackbody infrared radiation. Isolated atoms and molecules emit lines and bands from which they can be identified.

Calculation: Emission from warm gas seen in an ‘atmospheric window’ – wavelength $2.2\text{ }\mu\text{m}$.

Energy of Photon = Planck’s Constant $\times$ Speed of Light / Wavelength

Substituting: Energy = $6.63 \times 10^{-34} \times 3.0 \times 10^8 / 2.2 \times 10^{-6} = 9.04 \times 10^{-20} \text{ J}$ (0.56 eV)

Multiple of Visible Wavelength: 4.4

To make a mirror for any electromagnetic wave the surface must be smooth to at least one twentieth (0.05) of the wavelength to be reflected.

As the wavelength range of infrared is only slightly longer than that of visible light, infrared telescopes are almost identical to optical telescopes. The surface accuracy does not need to be quite so precise. However space-based IR telescopes are cooled to reduce IR emission from the telescope components.

The James Webb Space Telescope will be a large infrared telescope with a 6.5 metre primary mirror. Launch is planned for 2018. JWST will replace the Hubble Space Telescope. It will study every phase in the history of our Universe, ranging from the first luminous glows after the Big Bang, to the formation of solar systems capable of supporting life on planets like Earth and to the evolution of our own Solar System. It will be positioned at the Lagrangian Point 150 Gm from the Earth on the far side from the Sun where its sun-shield will keep it very cold. (NASA)

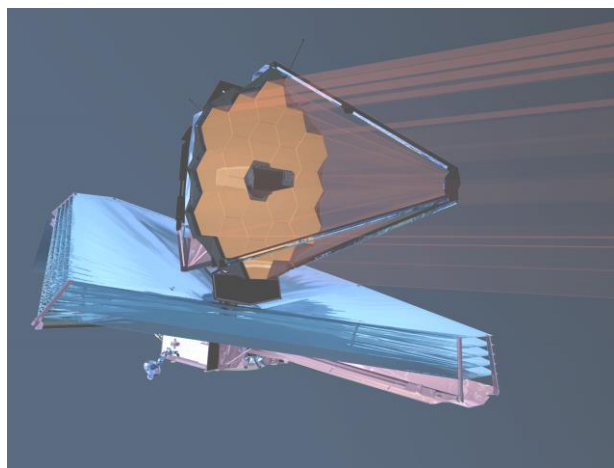


Figure 7: James Webb Space Telescope Graphic.
(NASA) www.nasa.gov

The Very Large Telescope in Chile and the UK Infrared Telescope on Hawaii are examples of ground-based facilities.

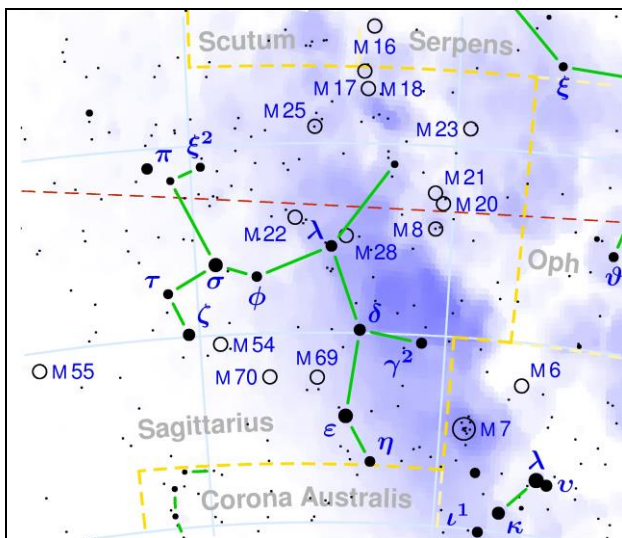


Figure 8: Celestial map of the constellation Sagittarius, the Wizard. (Torsten Bronger)

A visual light map of the region of the sky in the direction of the centre of our Galaxy. The map shows many nebulae, stars and dust clouds. The centre of our Galaxy is completely obscured.

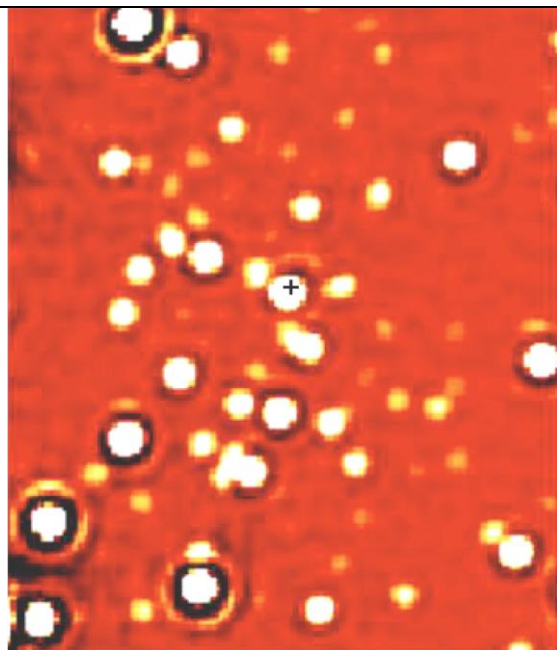


Figure 9: The Galactic Centre in the Infrared. (ESO)

Taken with one of the 8m VLT telescopes, this infrared image of a 2×2 arcsec area is centred on the position of the compact radio source SgrA* at the centre of our Galaxy (marked by a small cross). The image was taken at a wavelength $2.1 \mu\text{m}$ and the angular resolution (image sharpness) is about 0.060 arcsec. At about the same time, a star designated S2 came within 0.015 arcsec of the radio source. At the distance of the Milky Way Centre, 1 arcsec on the sky corresponds to 46 light-days. This star had a very close encounter with the black hole at the centre of our Galaxy! (ESO) www.eso.org

Examples:

- TV Remote Control – Point it at any electronic camera and press the buttons – see the IR LED flash.
- Passive infrared intruder detector – wire up the 12 volt supply and try walking towards it without the monitor LED switching on. This is almost impossible. The device detects the changes in the IR it is receiving from you and the room.

VISIBLE

Visible light waves are created when:

- Electrons move from one energy level to another in atoms
- Free electrons are accelerated and
- Hot surfaces emit blackbody radiation.

The surface of the Sun at 5700 K emits a significant amount of visible light as a black-body. Heated atoms just above the surface also emit spectral lines. Further above the surface, electrons are accelerated in the low density but very hot plasma. Helium was discovered in the line spectrum of the Sun.

Calculation: Emission from the surface of a Star – wavelength $0.5\ \mu\text{m}$.

Energy of Photon = Planck's Constant $\times$ Speed of Light / Wavelength

Substituting: Energy = $6.63 \times 10^{-34} \times 3.0 \times 10^8 / 0.50 \times 10^{-6} = 3.98 \times 10^{-16}\ \text{J}$ (2.48 eV)

Multiple of Visible Wavelength: 1.0

To make a mirror for any electromagnetic wave the surface must be smooth to at least one twentieth (0.05) of the wavelength to be reflected.

The mean wavelength of visible light is about $0.5\ \mu\text{m}$ so the surface accuracy needs to be 25 nm. Although small, an amateur telescope maker can achieve this with skill and patience! Large optical telescopes have a complex support system under the mirror to maintain its shape as the telescope tilts.



Figure 10: The sky over the VLT.

In this image of the night sky above Paranal, the Milky Way is clearly visible – the band of stars and dust clouds. At the centre of the image the two bright objects are Jupiter and Antares. Three of the four 8.2 m telescopes forming ESO's VLT are in view, with a laser beaming out from the fourth one, Yepun. The laser points directly at the Galactic Centre. The exposure time was 5 minutes and because the camera tracked the stars, the telescopes are slightly blurred. (ESO/Yuri Beletsky) www.eso.org

A wide-angle view inside the telescope enclosure. The telescope is Antu, one of the four that make up the VLT, with the ISAAC instrument at Nasmyth A focus. Each night about the time of sunset, the enclosure is opened and the telescope with its instruments is prepared for the night's observing run.



Figure 11: Telescope Antu. (ESO)

Telescopes can see very faint and very small objects in our Solar System.

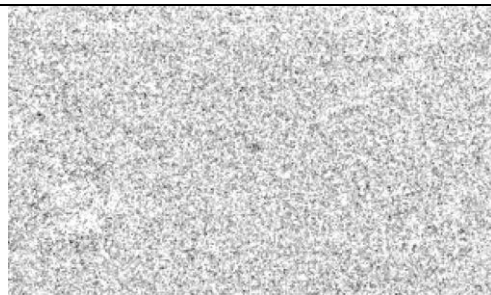


Figure 12: Comet Halley. (ESO)

The faint, star-like image of Comet Halley, observed with the VLT in 2003. 81 individual exposures from the 8.2 m VLT telescopes with a total exposure time of about 9 hours were combined to show the magnitude 28.2 object. Comet Halley was about 28 AU from the Sun. All images of stars and galaxies in the field were removed during the extensive image processing needed to produce this unique image. (ESO)

VLT observations of the double asteroid (90) Antiope during 2004. The VLT's adaptive optics system produced these very detailed images. The two components of the asteroid are bound by gravity. They are separated by 171 km and orbit each other every 16.5 hours. (ESO)

www.eso.org

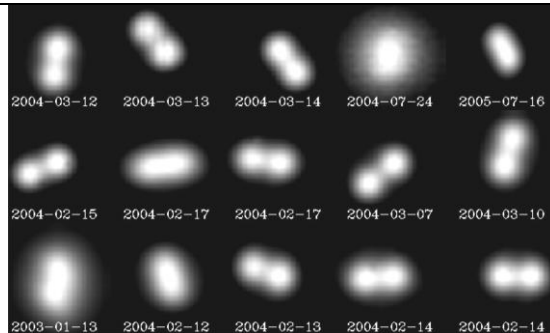


Figure 13: Asteroid Antiope. (ESO)

Activities:

- Use a spectrometer. e.g. Project Star Spectrometers www.starlab.uk.com
- Observe Solar Spectrum – quite possible even when cloudy – just point at the cloud and see the absorption lines, particularly in the green part of the spectrum.
- Dimmable tungsten lamp to show blackbody peak shift. When dim, its peak output is in the red part of the spectrum. When bright, its peak is in the yellow part of the spectrum.

ULTRAVIOLET

Ultraviolet waves are created when:

- Electrons move from one energy level to another in atoms
- Free electrons are accelerated and
- Hot surfaces emit blackbody radiation.

The surface of the Sun at 5700 K emits a significant amount of UV as a blackbody. Heated atoms just above the surface also emit spectral lines. Further above the surface, electrons are accelerated in the low density but very hot plasma.

Calculation: Emission from excited hydrogen (Lyman α line) – wavelength 121 nm.

Energy of Photon = Planck's Constant $\times$ Speed of Light / Wavelength

Substituting: Energy = $6.63 \times 10^{-34} \times 3.0 \times 10^8 / 121 \times 10^{-9} = 1.64 \times 10^{-18} \text{ J}$ (10.2 eV)

Fraction of Visible Wavelength: 0.24

This short wavelength means that mirrors have to be polished very carefully. UV is absorbed by most glass, so lenses are avoided.

UV images are best made from satellites but can also be made at good sites on the surface of the Earth.

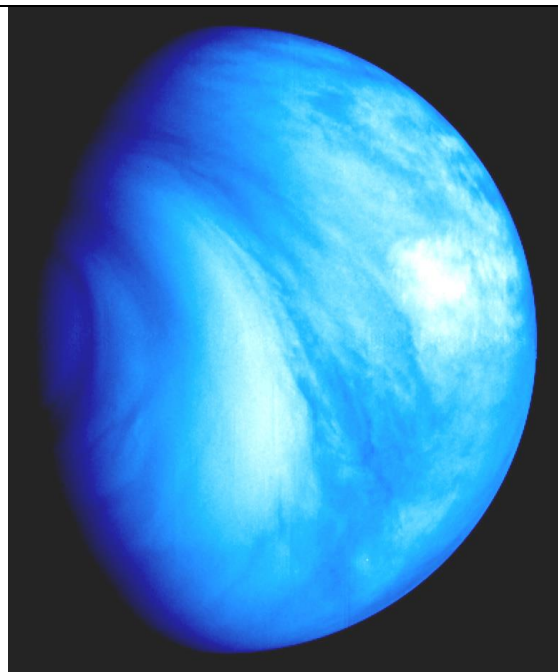


Figure 14: Venus in UV light. (ESA)

A false-colour image taken with the Venus Monitoring Camera on ESA's Venus Express. It shows the full view of the southern hemisphere from equator (right) to the pole. The south pole is surrounded by a dark oval feature. Moving to the right, away from the pole and towards the equator, we see streaky clouds, a bright mid-latitude band and mottled clouds in the convective sub-solar region. This image was taken in the ultraviolet at 365 nanometres on 23 July 2007 as Venus Express was 35 000 km from the surface of the planet. (ESA) www.esa.int

Sometimes the UV emissions from stars are so redshifted that they are seen in the visible part of the spectrum as shown in the figure below. There is a great deal of physics in the figure note!!

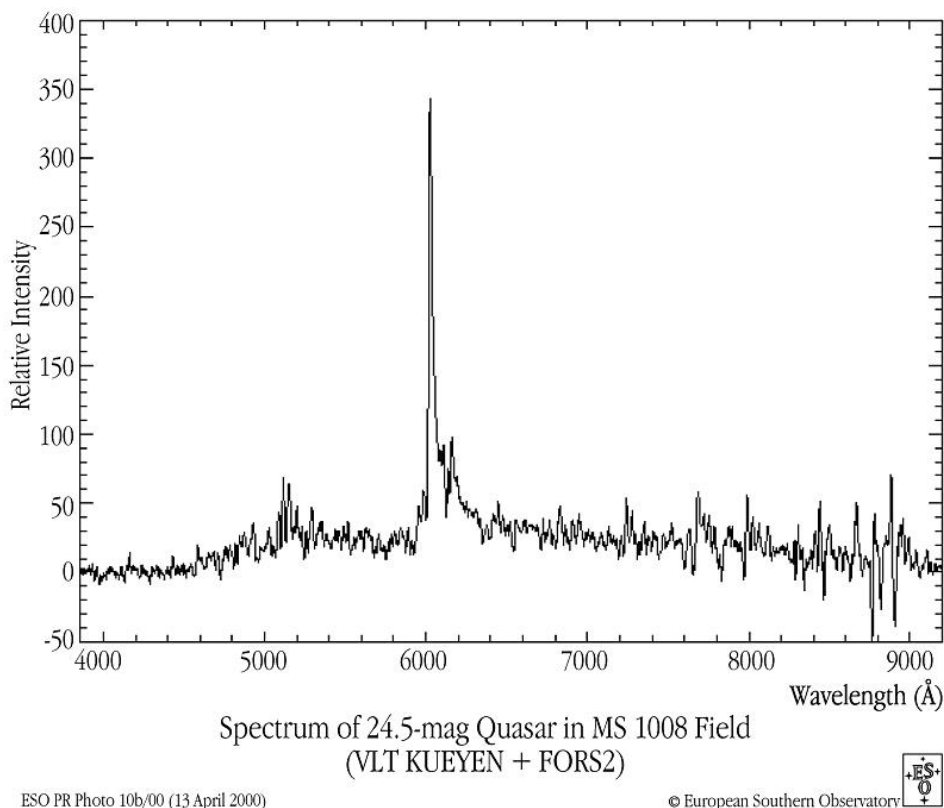


Figure 15: The spectrum obtained with FORS2 at KUEYEN of a quasar at redshift $z = 4.0$, lensed by the massive cluster of galaxies MS 1008. The redshifted Lyman-alpha line from hydrogen (rest wavelength $1216 \text{ \AA}$ (121.6 nm) in the far-ultraviolet part of the spectrum) is clearly seen in emission at $6025 \text{ \AA}$ (602.5 nm) as a high peak in the red spectral region. Another emission line, from four times ionized nitrogen (rest wavelength $1240 \text{ \AA}$), is seen in the right wing of the Lyman-alpha line. The spectrum was obtained with two hours of exposure through a 1.0 seconds of arc slit in good atmospheric conditions (seeing: 0.6 seconds of arc). (ESO)

Home Examples:

- UV Fluorescent Lamp (black light lamp) – checking bank notes – compare a real bank note with a piece of normal white paper – note the fluorescent additive in the ordinary paper.
- The fluorescence effects in disco lighting
- Sunburn and Sun beds and
- Fabric Deterioration. Bleaching of dyes in sunlight. Leave samples of coloured cloth and paper in a sunny window for a few weeks. Fold so that one half is exposed and the other half covered, then compare.

X-RAYS

X-rays are created when:

- Electrons move from outer to inner orbitals in atoms
- Free electrons are violently accelerated and
- Very hot surfaces emit blackbody radiation.

The surface of the Sun at 5700 K emits some X-rays as a blackbody. Heated atoms above the surface also emit spectral lines – emissions from Iron are often studied. Further above the surface electrons are violently accelerated in the low density but very hot plasma.

Calculation: Emission from 60 kV Medical X-ray Machine – wavelength 20.7 pm.

Energy of Photon = Planck's Constant $\times$ Speed of Light / Wavelength

Substituting: Energy = $6.63 \times 10^{-34} \times 3.0 \times 10^8 / 2.07 \times 10^{-11} = 9.61 \times 10^{-15} \text{ J (60 keV)}$

Fraction of Visible Wavelength: $1/24200$

Can you make a mirror that will reflect X-rays? Are aluminium atoms close enough together to act as a mirror for X-rays? Calculation of the spacing of aluminium atoms.

The atomic mass of aluminium is 27 g mole^{-1} . The density of aluminium is 2.7 g cm^{-3} . Avogadro's Number (the number of particles in one mole) is 6.02×10^{23} .

From this data, the volume of one mole of aluminium is $27/2.7 = 10 \text{ cm}^3$.

Consider this as a cube. The length of one side of this cube is $10^{1/3} = 2.15 \text{ cm}$.

In this length there are $(6.02 \times 10^{23})^{1/3} = 8.44 \times 10^7$ atoms.

Hence this spacing of aluminium atoms is $2.15/8.44 \times 10^7 = 2.55 \times 10^{-8} \text{ cm} = 255 \text{ pm}$.

This estimate is in good agreement with the face-centred cubic lattice length of 405 pm.

Now the wavelength of the X-rays above is 20.7 pm so a simple aluminium surface is not smooth enough to act as a mirror.

However, if X-rays strike the surface with an angle of incidence of say 89.8° the spacing is reduced by the cosine of this angle which is 0.00175. The aluminium atoms then seem to have a spacing of about 1 pm which would be small enough to act as a mirror. This is why X-ray mirrors are always used at "grazing incidence".

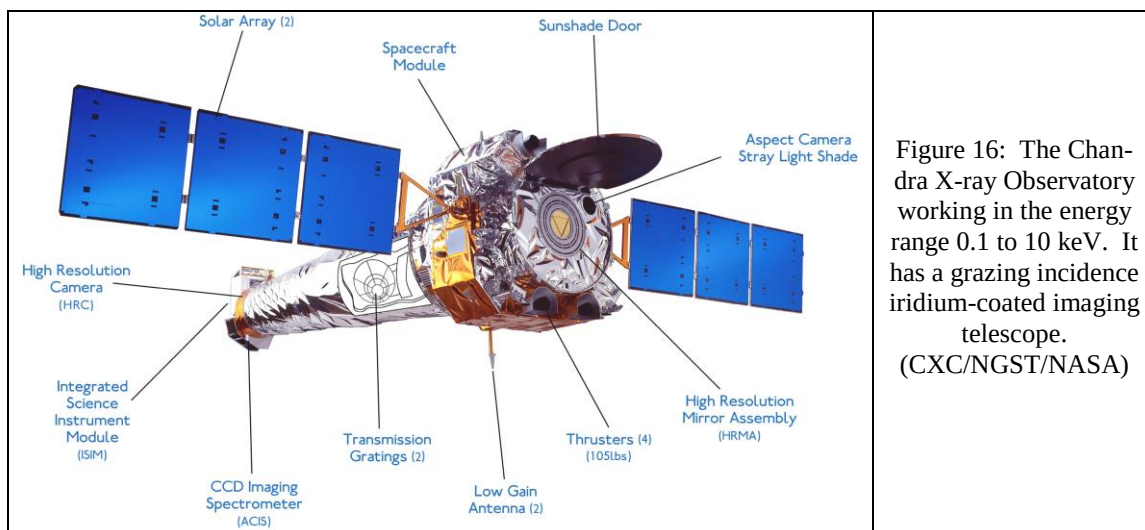


Figure 16: The Chandra X-ray Observatory working in the energy range 0.1 to 10 keV. It has a grazing incidence iridium-coated imaging telescope. (CXC/NGST/NASA)

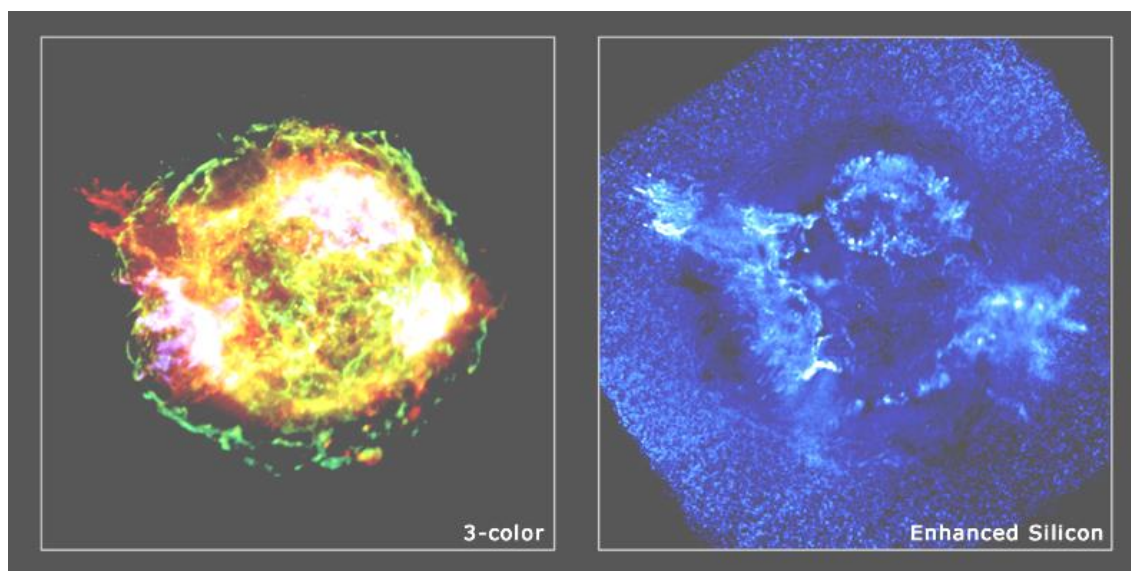


Figure 17: Images of the supernova remnant Cassiopeia A. The one million second image shows a bright outer ring (green) ten light years in diameter that marks the location of a shock wave generated by the supernova explosion. A large jet-like structure that protrudes beyond the shock wave can be seen in the upper left. In the accompanying image, specially processed to highlight silicon ions, a counter-jet can be seen on the lower right. Surprisingly, the X-ray spectra show that the jet and counter-jet are rich in silicon atoms and relatively poor in iron atoms. This indicates that the jets formed soon after the initial explosion of the star, otherwise, the jets should have contained large quantities of iron from the star's central regions. (NASA/CXC/GSFC/U.Hwang et al.)

One of the first X-ray sources discovered was Cygnus X-1. It is an X-ray binary star system in the constellation of Cygnus, the Swan. The visible object is a 9th magnitude blue supergiant star. The radial velocity curve shows an orbital period of a little less than a week. The fact that Cygnus X-1 is a strong X-ray emitter and that the optical and X-ray emission vary on very short time scales (as short as one one-thousandth of a second) gives us our best candidate for a nearby Black Hole.

Home Example: Medical X-rays. X-ray of a snake that has eaten two light bulbs – obviously a supporter of the Dark Skies campaign! See appendix.

GAMMA RAYS

Created in the most energetic events in the Universe.

Calculation: Emission from Nickel-56 formed in supernovae – wavelength 7.86 pm.

Energy of Photon = Planck's Constant $\times$ Speed of Light / Wavelength

Substituting: Energy = $6.63 \times 10^{-34} \times 3.0 \times 10^8 / 7.86 \times 10^{-12} = 2.53 \times 10^{-14} \text{ J}$ (158 keV)

Fraction of Visible Wavelength: 1/63600

At a wavelength of a few picometres or less, no surface will act as a mirror. Alternative methods have to be found to make telescopes. There are two main ways:

i) Pair-production in a satellite-based detector or



Figure 18: The Fermi Gamma-Ray Space Telescope ready for launch. (NASA)

The telescope is a powerful space observatory that will explore the Universe's ultimate frontier. It is collecting data on how black holes accelerate jets of material to nearly light speed and help crack the mystery of stupendously powerful explosions known as gamma-ray bursts.

It is studying the cosmos in the energy range 10 keV to 300 GeV.

www.nasa.gov

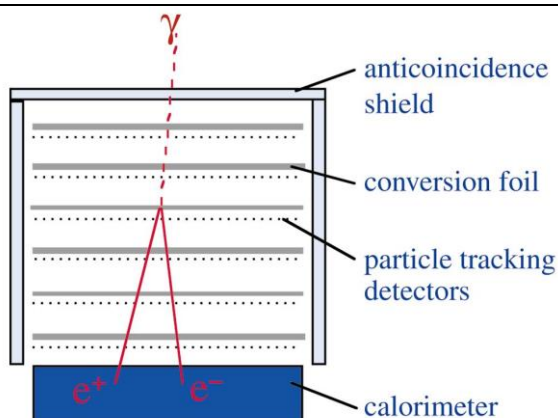


Figure 19: A cut-away of the Fermi Large Area Telescope instrument. (NASA)

This device detects gamma rays by pair-production. When a gamma ray hits a layer of tungsten in the detector, it creates an electron and positron pair. These particles in turn hit other layers of tungsten creating further particles and so on. The direction of the incoming gamma ray is determined by tracking the direction of these cascading particles back to their source using high-precision silicon detectors. A separate detector counts up the total energy of all the particles created. Its energy range is 20 MeV to 300 GeV.

ii) Čerenkov light flashes in the upper atmosphere are observed from the ground.

MAGIC (Major Atmospheric Gamma-ray Imaging Čerenkov Telescope) is a pair of imaging telescopes situated at the Roque de los Muchachos Observatory on La Palma, one of the Canary Islands, at about 2200 m above sea level.



Figure 20: The two Magic Telescopes with the massive new optical 10.2 metre Gran Telescopio Canarias in the background to the right. (Instituto de Astrofísica de Canarias) www.magic.iac.es

Čerenkov radiation is created when a particle passes through a material at a speed faster than the speed of light in that material. In air, this means that the particle must be travelling very close to the speed of light.

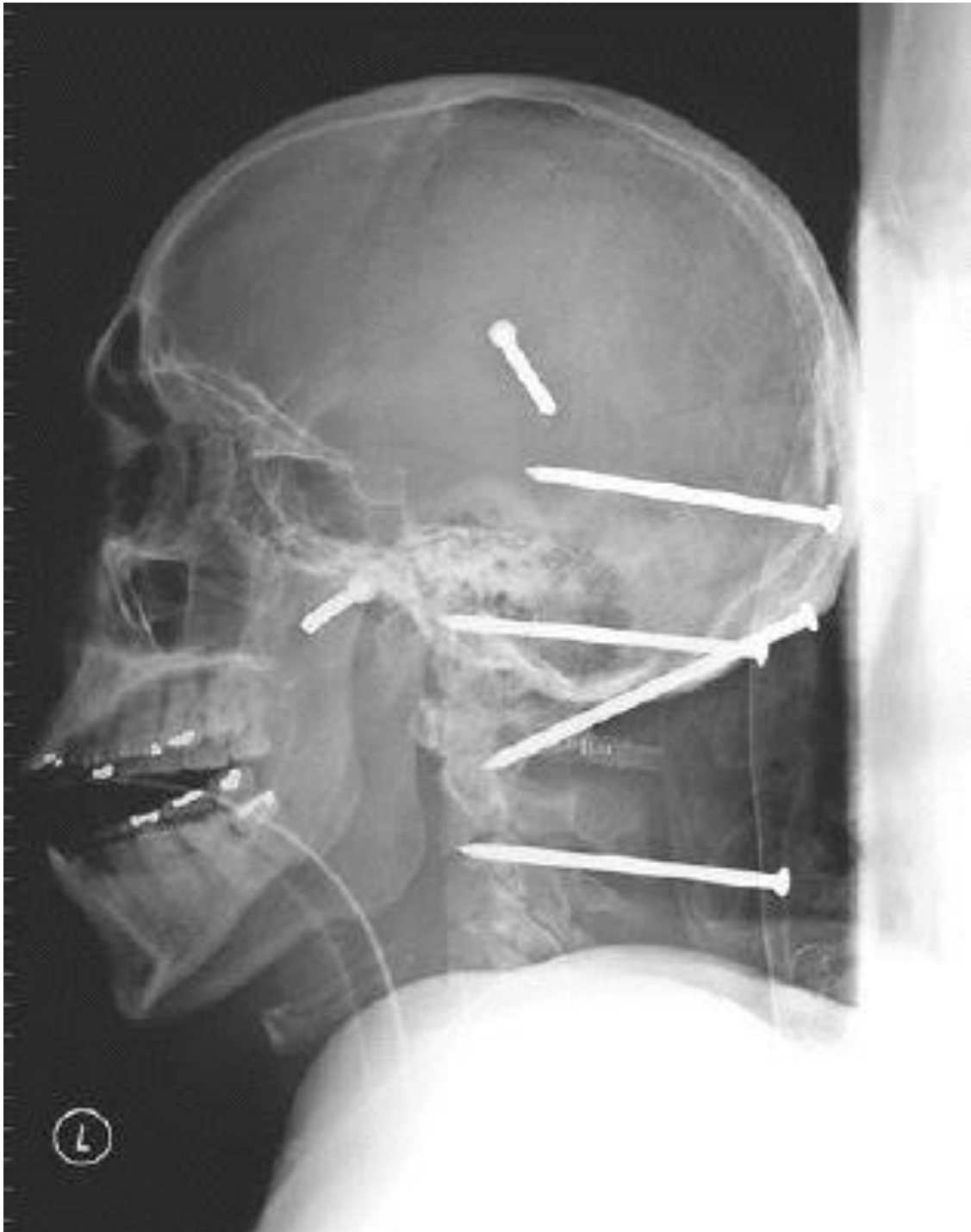
The MAGIC telescopes are sensitive to cosmic gamma rays with energies between 50 GeV and 30 TeV. They detect particle showers released by cosmic gamma-rays, observing the Čerenkov radiation, seen as faint flashes of light radiated by the charged particles in the showers. With a diameter of 17 meters they are the largest in the world.

MAGIC has found pulsed gamma-rays at energies higher than 25 GeV coming from the Crab Pulsar and very high energy cosmic rays from the quasar 3C279, which is 5 billion light years from Earth.

Home Examples of Radioactive Sources

- Low-Salt (mainly KCl) and Garden Fertilizer contain Potassium-40 which is a gamma ray emitter
- Granite Worktops in kitchens contain Uranium which emits Alpha and Gamma rays
- Radioactive isotopes formed during supernova explosions and found on Earth include Al-26, K-40, Ti-44, Ni-56 and Fe-60. [End]

Appendix: X-ray images from the web.



An accident with a nail gun.



A snake that swallowed two light bulbs! A supporter of the Dark Skies campaign!!