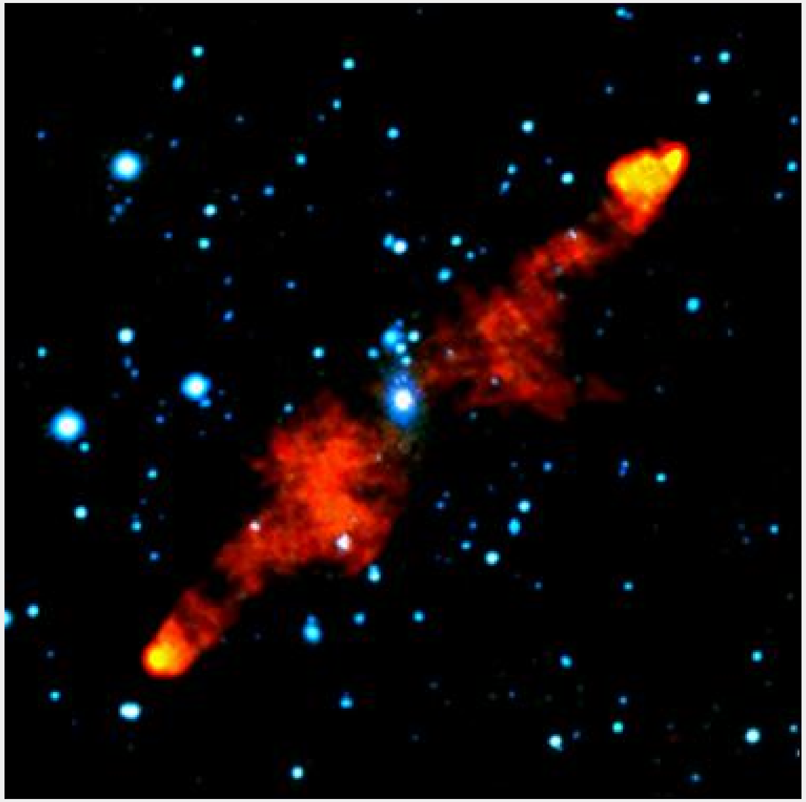
Mechanisms of Radio Emission: Thermal and Non-Thermal Radio Emission



Credit: A. Koekemoer, R. Schilizzi, G. Bicknell and R. Ekers (ATCA)/ATNF

Summary

In the last Activity, we looked at processes that resulted in radio line emission. In this Activity, we will investigate:

- flux and the importance of plotting spectra;
- processes that result in continuum emission, including:
  - **1.** thermal processes, which depend on the temperature of the emitter (eg. blackbody radiation); and
  - **2.** non-thermal processes, which do not depend on the temperature of the emitter (e.g. synchrotron radiation).

We will also learn about polarisation and Faraday rotation.

Classifying emission types

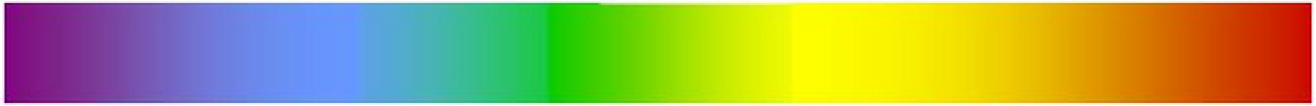
In the last Activity we looked at a number of processes that resulted in the creation of emission lines at radio wavelengths.

These primarily involved changes in the quantum state of an atom, such as the movement of electrons between energy levels and the spin-flip transition (i.e. the 21 cm line of atomic hydrogen), and changes in the rotational states of molecules.

Let’s now time to turn our attention to continuum emission at radio wavelengths.

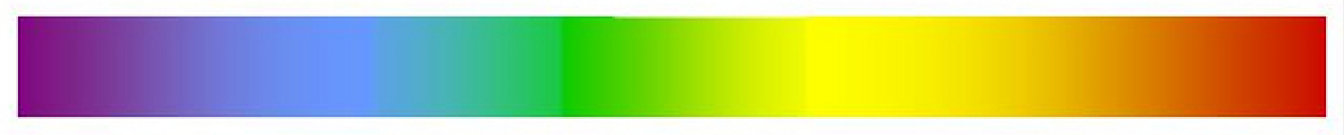
The visible continuum

As a quick reminder, this is what continuum emission at visible wavelengths looks like:



Unfortunately, we cannot provide a “true-colour” image of a radio continuum, as there is no such concept of colour when we move out of the visible part of the electromagnetic spectrum.

Even if we could make an analogous radio continuum image, it is limited in that it cannot easily show the *relative* amount of light at each wavelength.

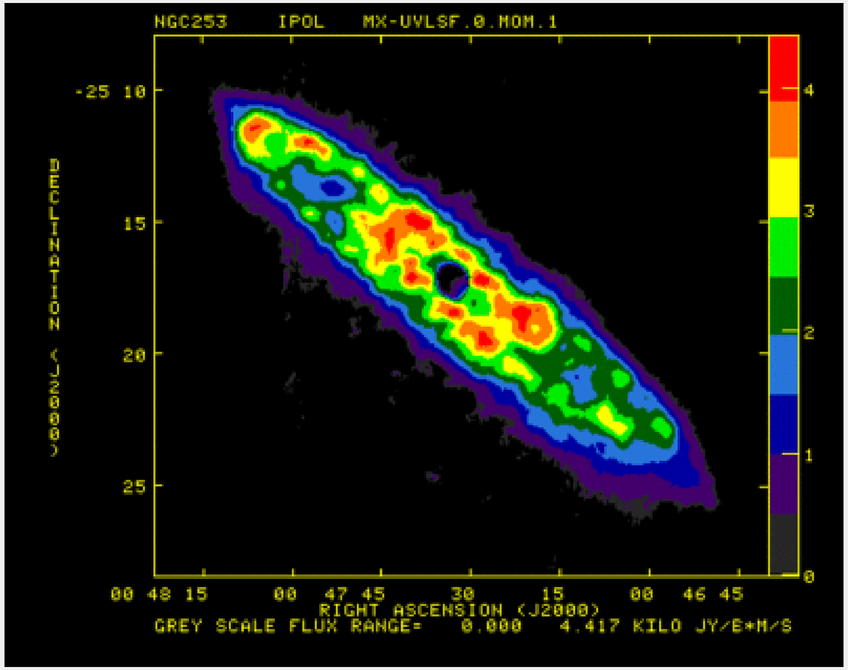


Is there more blue light? Or more green light? Or more red light?

Paint by numbers

One solution is to use a “false-colour” image. For a continuum image, we can assign a different colour to each wavelength. Or for an image at one particular wavelength (e.g. a specific radio emission line) we can assign a different colour depending on the intensity of the signal.

A 21 cm line image of the spiral galaxy NGC253 is shown on the right in false colour. Regions with lots of HI are coloured red, while regions with very little HI detected are coloured purple.

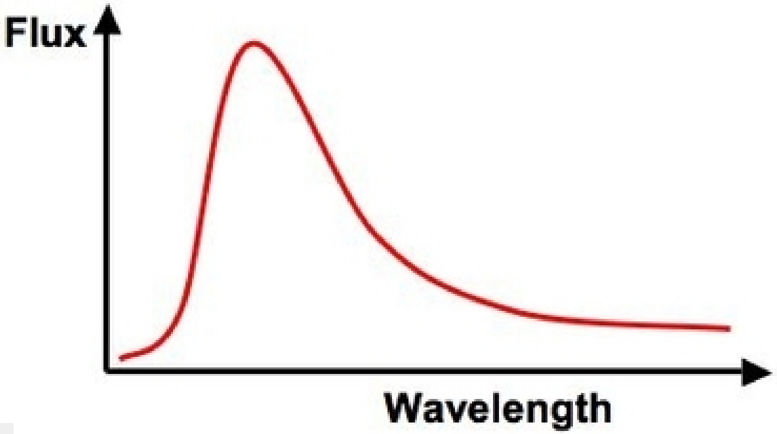


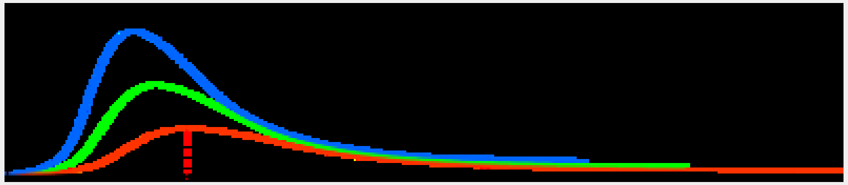
Credit: Koribalski, Whiteoak “& Houghton (1995)

Plotting a spectrum

An alternative method is to plot a spectrum of ***radiation flux*** versus ***wavelength*** or ***frequency***.

The exact shape of the spectrum (such as the peak wavelength with the most flux or the slope of the spectrum), can provide us with a great deal of information about the emission mechanism.

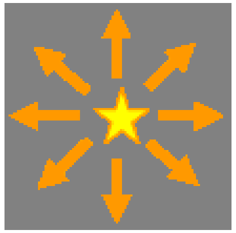




Flux (Vertical) vs wavelength (horizontal). The blue line represents hotter stars and the red cooler ones.

But before we go too much further, we need to learn a little more about flux.

Flux and the Jansky



Consider the simple case where we have a source which is emitting energy in all directions. The total energy emitted by the star per second is the (total) **luminosity**, L, measured in Watts [W].

The dish has finite collecting area and there is finite bandwidth for detection

We observe the source using a detector (e.g. a radio telescope) that has a finite collecting area (in units of m^2) and a finite frequency range over which it can detect photons (in units of Hz). How does that affect the energy that is actually detected from the source?

Radiant flux and luminosity

The telescope will intercept a fraction of the total luminosity depending on how far the telescope is from the source.

Flux is defined as the total radiation energy crossing a unit area per unit time within a particular narrow frequency range. We can think of the energy from the source as spreading out through space in series of concentric spheres.

Ignoring the frequency dependence for the moment, at a sphere of radius R from the source with luminosity *L*, the **radiant flux**, *F*, passing through this sphere is:

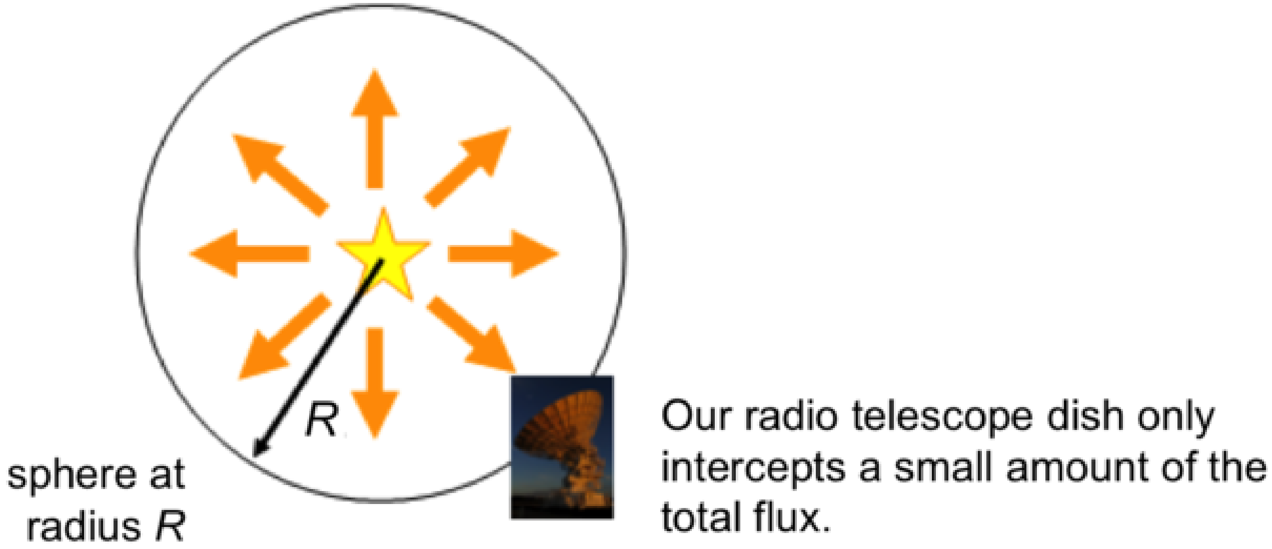
$$F = \frac{L}{4\pi R^2}$$

In this special case, the units of flux would be W/m^2 (using our hypothetical multi-wavelength telescope with an infinite observing bandwidth!)

This is an example of the inverse square law.

Flux at the telescope

The flux detected by a telescope is much less than the total flux of the source. This is because the collecting area of a telescope, such as the dish of a radio telescope, is very much smaller than the surface area of the imaginary sphere surrounding the source!



The Jansky

In radio astronomy it is common to see fluxes quoted in Jansky, where:

$$1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$$

Now this seems like a tiny amount of energy, but as we'll see later it is appropriate for radio astronomy.

Here:

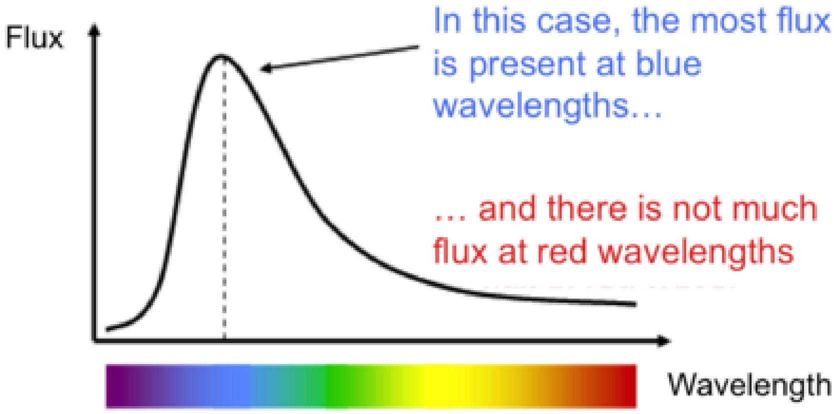
- W is the total amount of watts which is the number of Joules per second collected.
- m^{-2} is per square metre.
- Hz^{-1} is the number of Hertz over which the measurement is made.

So to work out the flux of a source we would measure the power in watts, divide by the number of square metres and divide by the bandwidth (in Hz). This would be a tiny number for every known radio source in the sky!

So we multiply by 10^{26} to get the answer in Jansky (often abbreviated as Jy).

Plotting a spectrum

Now that we have defined the flux from a source, let's look at our visible light continuum again. This time we will plot the spectrum:



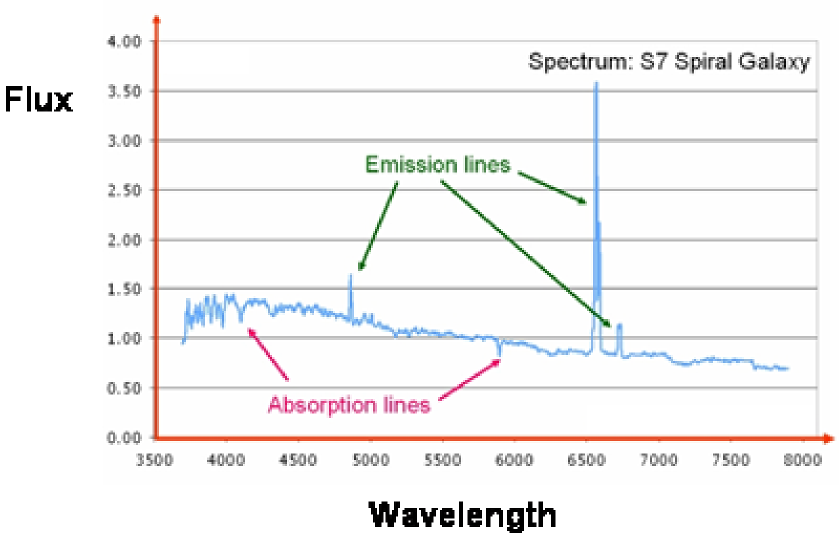
In this case, the most flux is present at blue wavelengths...

... and there is not much flux at red wavelengths

We can also plot a spectrum at radio wavelengths, as all we need to do is measure the amount of flux over a different frequency or wavelength range.

Emission lines

This is the visible spectrum of a typical spiral galaxy:



It has both emission and absorption lines[1].

In this spectrum the emission lines are very prominent whereas the absorption lines are more subtle.

[1] Click here to learn more about absorption lines

Continuum emission

Like all electromagnetic radiation, continuum emission results from the accelerations ofcharged particles. But while line emission results from atomic processes that only have very specific quantised energies, continuum emission results from processes where the energy exchange is not quantised and so the photons emitted may have a continuous energy distribution.

There are two main types of continuum emission:

- thermal radiation.
- non-thermal radiation.

Thermal radiation

Thermal means that the radiation is dependent solely on the *temperature* of the emitter.

Non-thermal radiation involves other processes. In this Activity we are going to look at two specific examples of continuum radiation: thermal blackbody radiation and non-thermal synchrotron radiation[1].

At short radio wavelengths, thermal emission sources dominate the sky, while non-thermal process dominate at long radio wavelengths.

As we shall see, the shape of the spectrum of thermal and non-thermal radiation differs, making it easy to determine the emission mechanism of a source.

[1] Other types of radio thermal radiation include free-free radiation, and other types of non-thermal radio radiation include maser emission. We will learn more about these types of continuum radiation in a later Activity. (Note that there are many of types of thermal and non-thermal radiation mechanisms that do not emit radio photons, such as thermal Compton scattering and non-thermal Bremsstrahlung, both of which emit X-ray photons.)

Thermal radiation and blackbodies

All objects with temperatures above absolute zero[2] have some internal motion: the atoms in solids are vibrating and the molecules in gases are zooming around and bumping into each other. The hotter the body, the faster the vibrations or the more collisions occur.

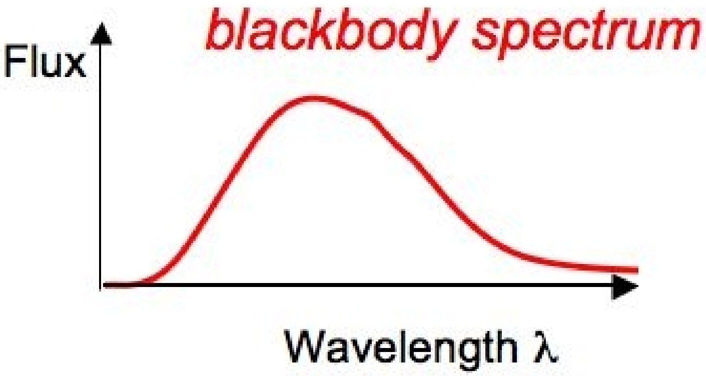
Since accelerating charged particles (like the electrons in atoms) emit electromagnetic radiation, **all** bodies above absolute zero emit ***thermal radiation***.

Thermal radiation just means that a body's emission spectrum is determined by its temperature. The simplest (and most ideal) case of thermal emission is that of a ***blackbody***.

[2] Absolute zero = 0 K = -273 °C

Perfect blackbodies

An object which is capable of absorbing all of the radiation which happens to fall on it is called a **perfect blackbody**. In turn, such an object will ***emit*** a smooth spectrum of radiation which peaks at a frequency (or wavelength) dependent only on the object's temperature.



Blackbodies also have the following characteristics:

- they emit some energy at *all* wavelengths;
- the higher the temperature of the blackbody, the more energy it emits; and
- the higher the temperature of the blackbody, the shorter the wavelength at which the maximum energy is emitted.

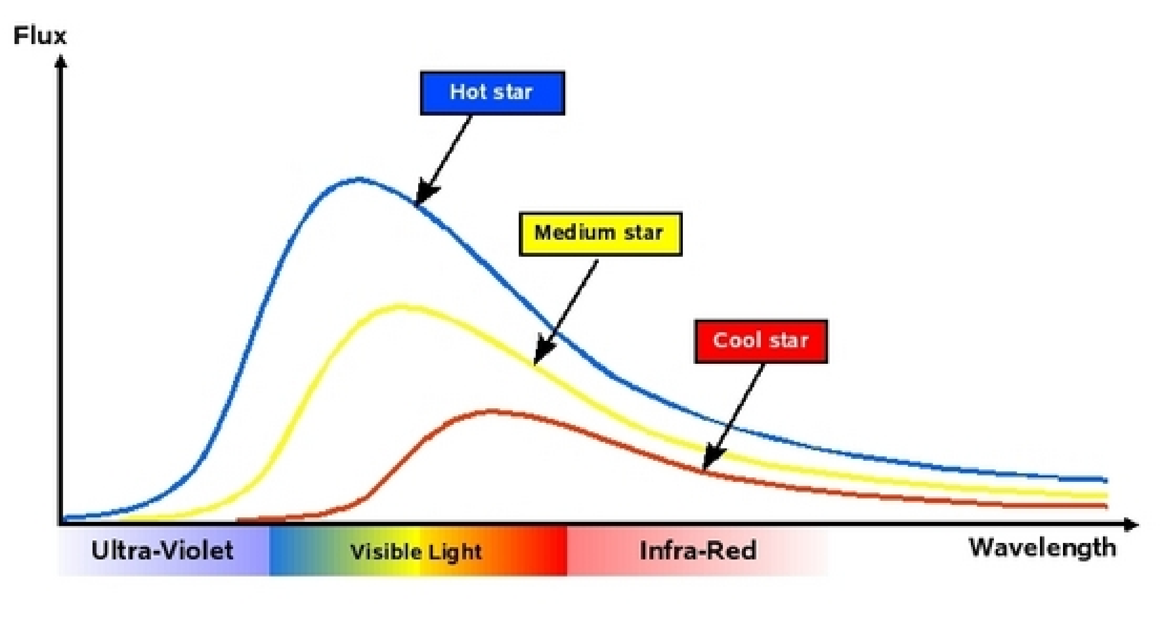
Wien's law

There are two important laws that describe blackbody radiation.

Wien's law states that the peak of the radiation spectrum λ_{max} is inversely proportional to the temperature T of the black body.

$$\lambda_{\max} = \frac{2.898 \times 10^6}{T}$$

where λ is in nanometers and the temperature T is in Kelvin.



As the source temperature increases the peak wavelength decreases. This is why hot stars are blue and cool stars are red.

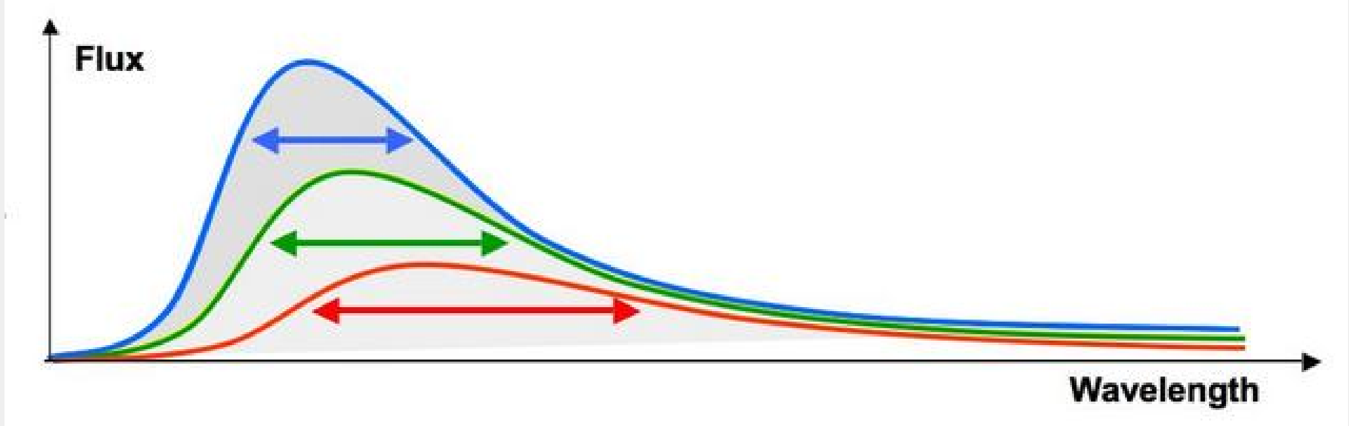
The Stefan-Boltzmann law

The Stefan-Boltzmann law relates the energy output from a blackbody to its temperature, where the energy output is just the area under the flux-wavelength curve. The hotter a body is, the more it radiates.

The total amount of energy a blackbody of area *A* emits per second (i.e. its luminosity or power, *P*) is related to temperature *T* by:

$$P = A\sigma T^4$$

Here σ = 5.67 × 10^{-8} J s^{-1} m^{-2} K^{-4}, which is the Stefan-Boltzmann constant.



Flux vs wavelength for a selection of blackbodies. As the temperature decreases the area under the curve is reduced dramatically.

We can use both the Stefan-Boltzmann law and Wien's law to determine the temperature of a thermal source once its luminosity is known.

Wien's law shows us that hot stars emit thermal radiation in the visible band, while cool planets (and people!) emit thermal radiation in the infrared region.

In the radio range we will only be able to detect thermal radiation from very cool sources, with temperatures less than 10 K. The entire Universe emits thermal radiation that peaks in the microwave wavelength, with a temperature of only 2.7 K.

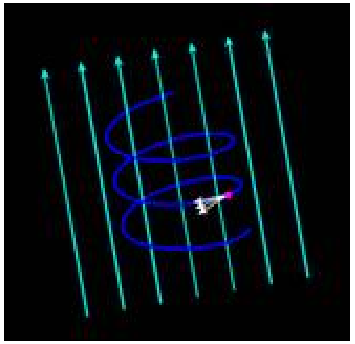
Non-thermal radiation

While **thermal emission** depends on the temperature of the emitting source, **non-thermal emission** depends on other things, such as the relative proportions of excited states of atoms and magnetic field strength.

Examples of non-thermal radiation include synchrotron radiation, maser emission, and Compton scattering. Both synchrotron and maser emission are important in radio astronomy so we will look at them both in some detail. In this Activity we will learn about synchrotron radiation, and leave maser emission to the next Module.

Synchrotron radiation

If a charged particle (usually electrons) travelling near the speed of light passes through a magnetic field, the particle spirals along the field lines in helical paths. This change in their direction of motion means that they are accelerating, and they will therefore emit radiation.

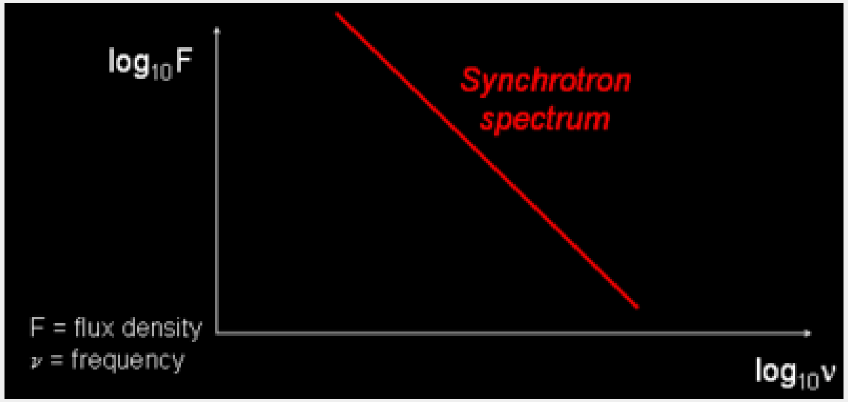


This type of radiation is called **synchrotron radiation.**

Since there will be many electrons with a range of energies that encounter the magnetic field, the radiation emitted covers a wide frequency range and so synchrotron radiation is seen as continuum emission.

Synchrotron vs thermal

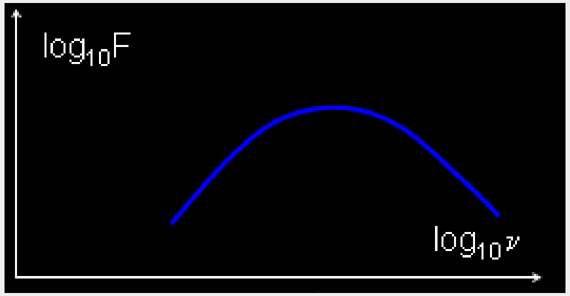
Note that synchrotron radiation has relatively few high energy photons compared to low energy photons. When plotted on a log-log scale it's continuum spectrum looks like this:



Typical synchrotron spectrum.

Note that we have made a change from wavelength to frequency.

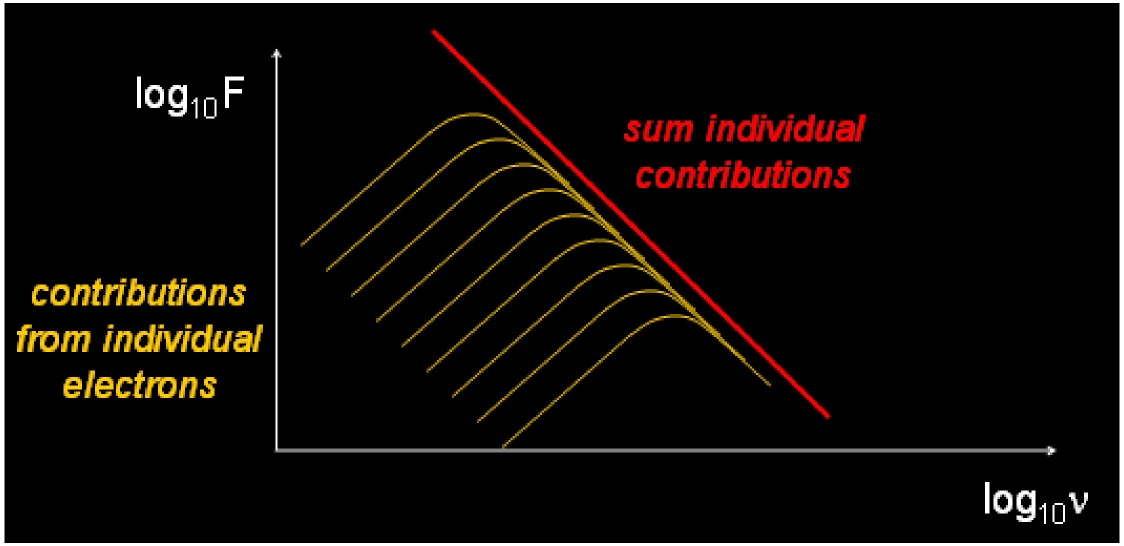
Compare this to a typical thermal spectrum:



Typical thermal spectrum.

Synchrotron emission spectrum

The spectrum of synchrotron emission results from summing the emission spectra of individual electrons.



As the electrons spiral around the magnetic field, they emits radiation over a range of frequencies. Each emitted photon has a frequency that is determined by the speed of the electron at that instant.

Spectral Index

If over some finite frequency range we can describe the amount of flux *F* as a function of frequency (ν) by the formula:

$$\log_{10} F \sim \alpha \log_{10} \nu$$

where α is a constant, we call α the ‘spectral index’.

We say that the flux has a ‘power law dependence’ on frequency given by α.

If $\alpha \sim 0$ we say the source has a flat spectral index.

If $\alpha < 0$ we say it has a negative spectral index.

If $\alpha << 1$ we say it has a steep spectral index.

Since synchrotron radiation is strongest at low frequencies (long wavelength) it can be detected with radio telescopes.

For a reminder of the logarithmic scale, follow this link.

Synchrotron properties

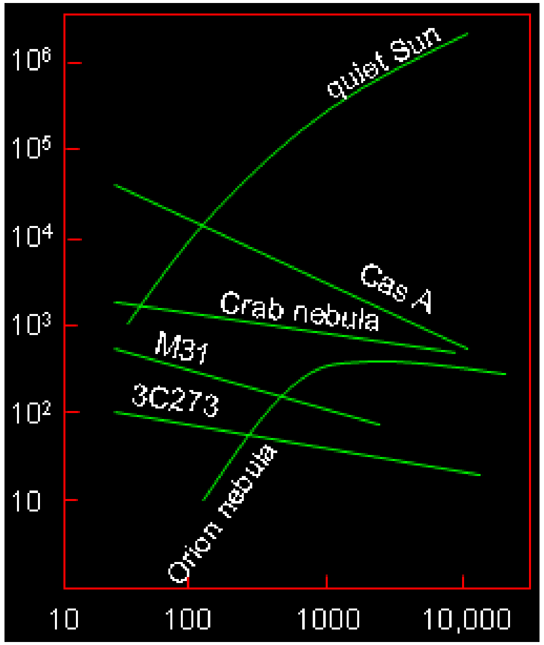
Some properties of synchrotron radiation include:

- It is extremely intense and highly collimated radiation, which means that the radiation seems to be coming from a thin cone.
- It is emitted over a wide range of energies, producing a wide energy spectrum.
- It is highly polarised (which we'll discuss in a moment), with the degree and orientation of the polarisation providing information about the magnetic fields of the source.

Synchrotron radiation can be observed anywhere there are fast-moving electrons and magnetic fields.

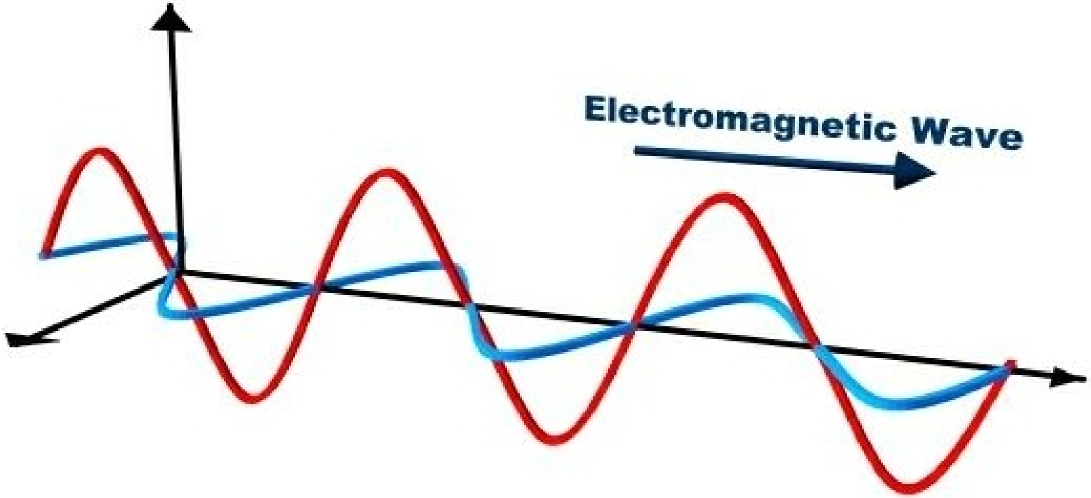
This occurs, for example, in supernovae and pulsars (which are remnants of massive stars), around planets with strong magnetic fields, in the jets emanating from active galaxies, and near black holes.

Here we compare the spectrum of two thermal sources (Orion Nebula and the quiet Sun) with synchrotron emission from the quasar 3C273, the galaxy M31, and the supernova remnants Crab nebula and Cassiopeia A. The shape of the two types of emission clearly differ.



Polarisation

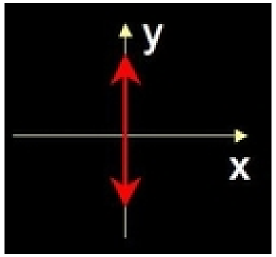
Recall that an **electromagnetic wave** is a self-propagating disturbance of electric and magnetic fields at right angles to each other, with both fields perpendicular to the direction of propagation.



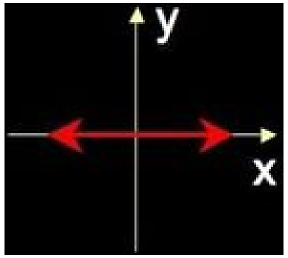
Properties of light

Light is a *transverse wave*, which means that the wave vibrates perpendicular to the direction of propagation.

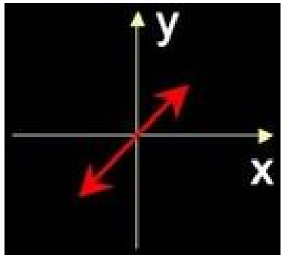
If a beam of light is travelling out of the screen towards you (consider for now just the electric field), it can vibrate either up and down in the vertical plane,



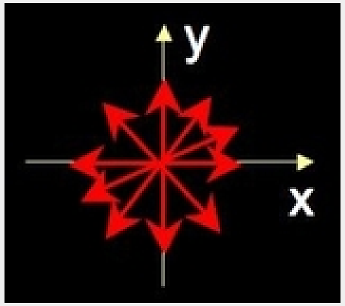
side to side in the horizontal plane,



or in any intermediate orientation.



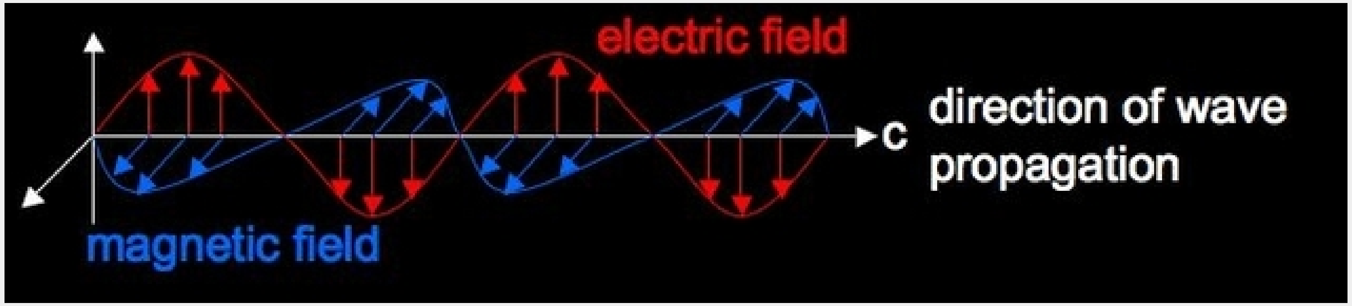
Normally, a ray of light contains a mix of waves of the same amplitude vibrating in all directions perpendicular to the direction of propagation. Such light is called **unpolarised**.



Unpolarised light

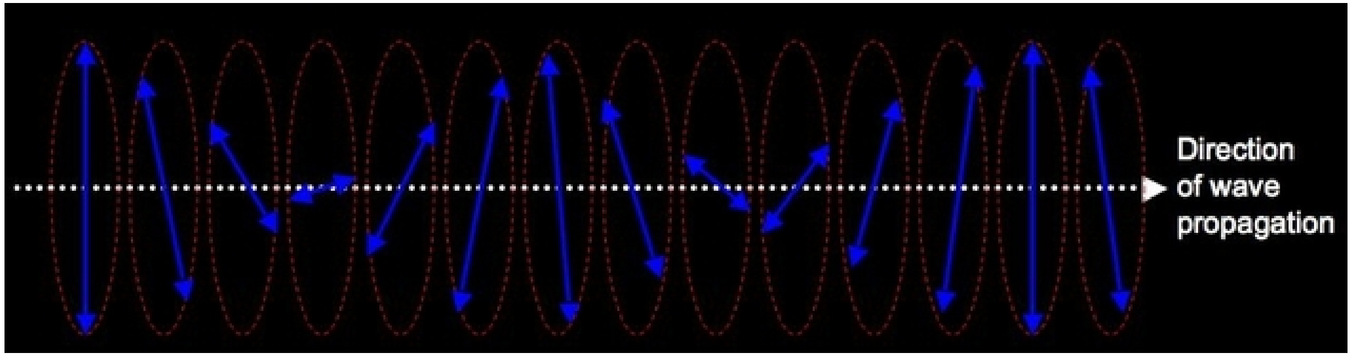
The orientation of the *electric field* defines the **polarisation** of electromagnetic radiation. If the vibrations have greater amplitude in a preferred direction, then the light is said to be *linearly polarised*, and can range from partially to totally polarised.

If the electric field always vibrates in just a single plane, the wave is said to be **plane polarised**.



Light comprises of oscillating electric and magnetic fields

The plane of vibration can also rotate as it propagates.

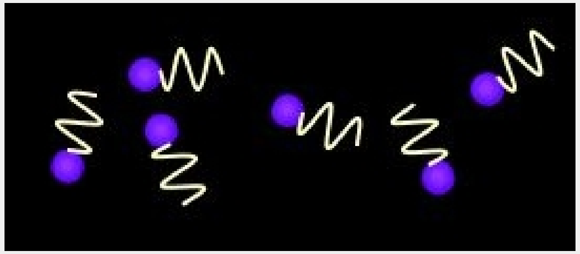


If the amplitude of vibration remains the same, the electric field will trace out a circle and the radiation is called **circularly polarised**.

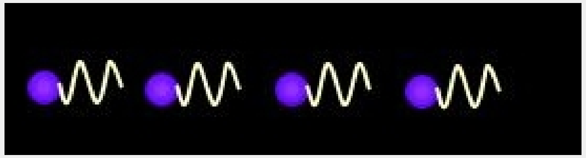
On the other hand, if the amplitude changes during propagation, the electric field traces out an ellipse, and the radiation is **elliptically polarised**.

Why is light polarised?

A light beam is usually made up of the superposition of many light waves emanating from many atoms in the source.



The atoms will generally be orientated randomly, so the direction of the electric fields will also be random and the light will be **unpolarised**.

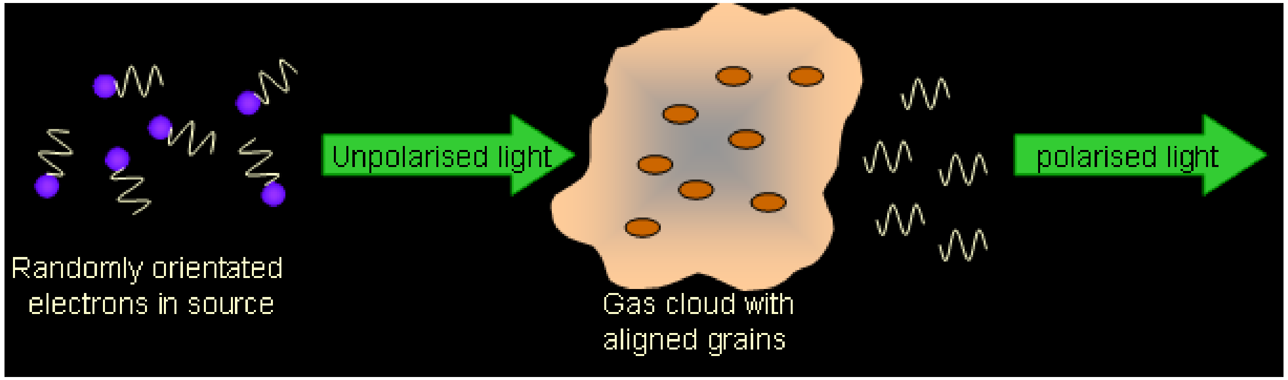


If the atoms are aligned, their electric fields will also be aligned and the radiation from such a source will be **polarised**.

The type of polarisation – whether linear, circular or elliptical – depends on what is happening to the atoms (or electrons) in the source.

Polarising light

For example, light scattered in a gas becomes partially polarised, which occurs in planetary atmospheres. Light scattered off interstellar grains that are aligned can also become partially polarised.



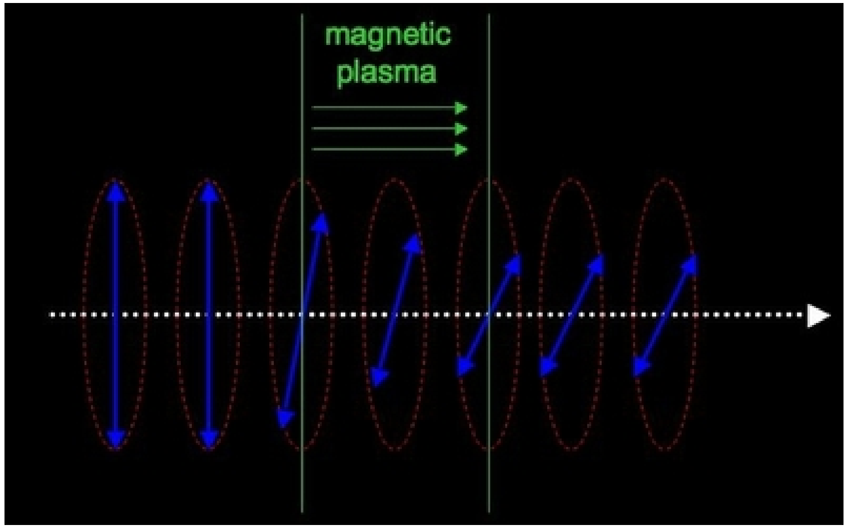
Circular polarisation is an indication of the presence of strong magnetic fields in the region where the light is emitted (making electrons spiral along on helical paths). Examples are found in the radio and visible emission from pulsars, supernova remnants and magnetic stars.

Faraday rotation

The plane of polarisation of linearly polarised radiation is rotated when the radiation propagates through a magnetised plasma. This effect is called **Faraday rotation**.

(The reason that the magnetic field rotates the polarisation is due to a complex propagation process of the electromagnetic wave which requires some high-level mathematics that is beyond the scope of this Unit!)

The magnetic field must be aligned with the direction of wave propagation.



The amount of Faraday rotation depends on four things:

- the mean electron density of the plasma;
- the mean magnetic field strength;
- the square of the wavelength of the radiation; and
- the distance travelled through the medium. The magnetic field must be aligned with the direction of wave propagation.

Putting it all together

The combined emission from a source, detected over a range of wavelengths (or frequencies), might result in a composite of all the processes we have looked at.

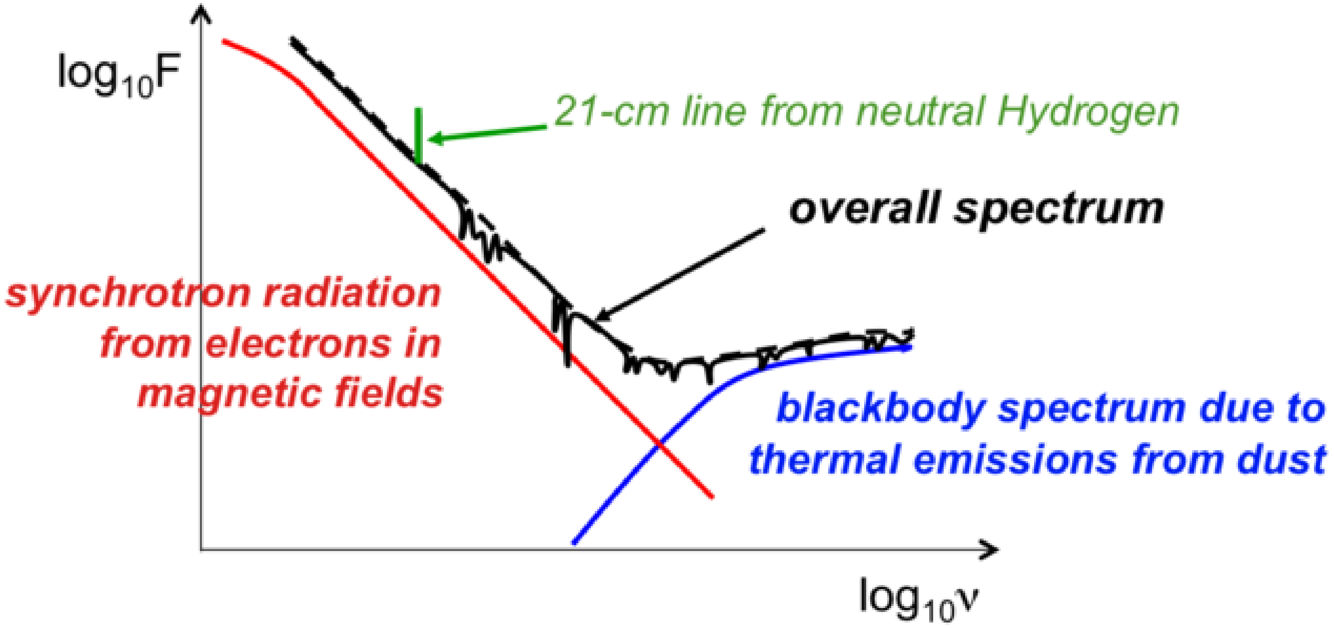
For example, a typical normal galaxy has a spectrum that contains:

- A component of synchrotron radiation at long wavelengths (low frequency) due to the galaxy's magnetic field.
- A blackbody spectrum at short wavelengths (high frequency) due to dust in the galaxy.
- 21 cm line emission from neutral hydrogen. And...
- Possibly some absorption lines as well.

On the next page, you can see the composite spectrum.

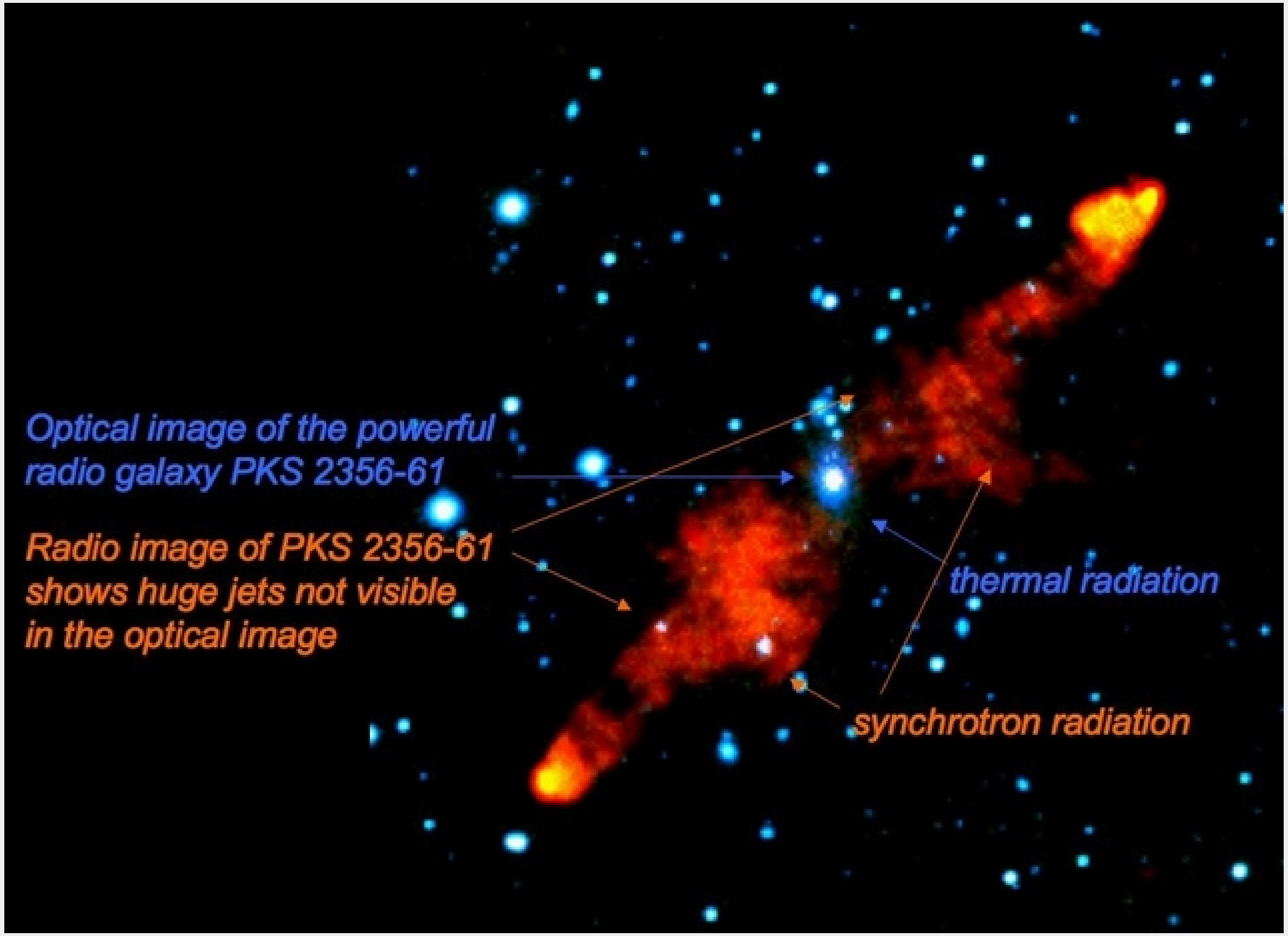
Composite radio spectrum

Composite spectrum for a typical normal galaxy observed over a wide range of frequencies, from radio to visible:



If we only observe the source at visible wavelengths, we would only get a part of the picture. The radio portion of the spectrum provides us with many clues about the nature and properties of the source.

The different emission mechanisms can dominate different regions of your source.



Optical/Radio composite image of the powerful radio galaxy PKS 2356-61

Credit: A. Koekemoer, R. Schilizzi, G. Bicknell and R. Ekers (ATCA)/ATNF

Observing continuum radiation

So now that we know the various mechanisms that produce continuum radiation, how do we actually observe it?

Unlike line emission, we do not have a specific frequency to tune our radio receiver to when we are doing continuum observations. Ideally, to gain the optimal amount of information from our source, we'd like to observe over as wide a range of frequencies as possible. Because of the design of radio correlators and receivers, we are usually limited to some set frequency range.

So, for example, you might be interested in the total flux from all radiation in your source between 2.5 cm and 3.5 cm, which you then call the "3cm continuum flux density". Thus you'll often see terms like the "7 mm continuum" and the "6 cm continuum".

The full spectrum?

To get a full spectrum of your source across the entire radio range would require you to observe across a range of radio bands.This must be done either (i) at different times, (ii) at different telescopes, or (iii) at telescopes with dual or multi-frequency observing capacity.

In reality this is very rare.

Radio sources

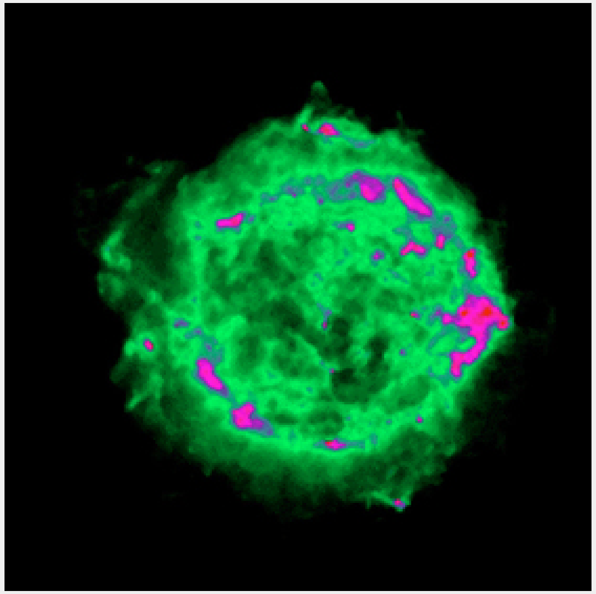
Now that we've learned a little about the radio end of the electromagnetic spectrum and have investigated some of the mechanisms of radio emission, what types of sources actually emit radiation in the radio range?

There are several sources of radio emission in our galaxy, the Milky Way.

- Interstellar atoms and molecules emit line emission at radio wavelengths. The first radio line discovered was the 21 cm line of atomic hydrogen, and since then many interstellar molecules have been discovered. We have learned a lot about the structure and composition of the Milky Way thanks to these radio lines.

More sources

- **Supernova remnants**, which are the remains of exploded stars, are sources of strong radio emission. They have very strong magnetic fields and so their radio emission is thought to be due to synchrotron radiation.



Radio image of supernova remnant Cassiopeia A

Credit: Chandra

- **Pulsars**, which are rapidly rotating neutron stars, are also strong radio emitters. They too have very strong magnetic fields and their radio emission is also probably synchrotron.

Still more sources

Extragalactic sources of radio emission include:

- **Radio galaxies**, which are usually giant elliptical and irregular galaxies. They emit more than a million times the radio energy of spiral galaxies!

Giant elliptical NGC 4881 in Coma

- **Quasars** (or quasi-stellar radio sources), which are extremely distant strong radio sources.
- There is also a small amount of background radio noise coming from every direction in the sky, known as the cosmic microwave background or **CMB**, which is the left over thermal radiation from the Big Bang.

We'll learn more about these and other radio sources in the next Module.

Summary

In this Activity, we have discussed flux - the total radiation energy crossing a unit area per unit time within a particular narrow frequency range - and plotting specta (flux against wavelength).

We also discussed continuum emission processes which result from the acceleration of charged particles. In continuum emission the energy is not quantised and so the photons emitted have a continuous energy distribution. We looked at thermal emission from blackbody radiation as well as non-thermal emission such as synchrotron radiation.

We also discussed polarisation, in which the direction of vibration of radiation are restricted, and Faraday rotation, which occurs when the plane of polarisation of linearly polarised light is rotated as it propagates through a magnetised plasma.

In the next Module we will learn about galactic sources of radio emission.