1 Scope

This article considers a number of radio emitting objects that can be observed by amateur radio astronomers using a modest range of equipment. The order in which these objects are discussed is largely determined by their distance from Earth and this is loosely related to their ease of detection.

Radio emissions generated within the Earth's Magnetosphere and Ionosphere are not considered here. Emissions such as Whistlers and Chorus are however of interest to amateur radio astronomers, and much has been written elsewhere about the impact of Solar X rays on the Ionosphere resulting in Sudden Ionospheric Disturbances (SIDs).

The strength and emission spectrum of a variety of distant radio sources are considered and related to the physical mechanism by which they are generated. This gives some insight into the range of processes by which naturally occurring radio emissions can be produced from sources within the Solar System to those out in intergalactic space.

Describing the equipment that can be used to detect these sources is not the main purpose of this article but is touched upon where appropriate, to illustrate the scale and technical complexity of instruments required to observe some sources.

2 Overview of source signal strengths and spectra

2.1 Signal strength

The signal strength from natural radio sources may be thousands of times smaller than those from radio and TV stations, which are usually around 100µV/m. Radio astronomers use power flux density as the unit of signal strength and this is in Watts per square metre per Hz (W m^{-2} Hz^{-1}). In honour of the first radio astronomer Karl Jansky, the very small value of 10^{-26}W m^{-2} Hz^{-1} is called 1 Jansky - or 1 Jy.

The relationship between typical power densities of some radio sources discussed in this paper is given in Figure 2.1. This illustrates the wide range of source signal strengths. Each source has a different signal strength as a function of frequency and in Figure 2.1 this is covered by representing the range of signal strengths as a coloured block.

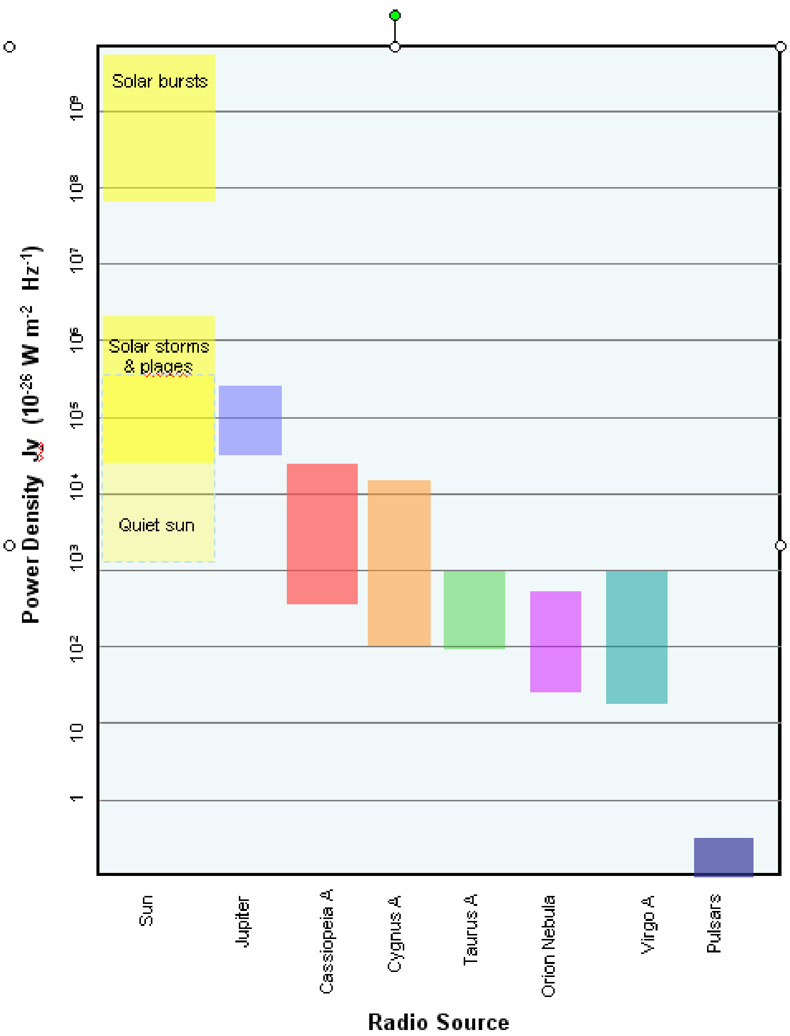


Figure 2.1 Power density of various radio sources

There are nearly eight orders of magnitude between the strongest and weakest sources that an amateur might detect. Very strong solar bursts can have strengths up to 10^9 Jy and an external radio galaxy like Virgo A may have a strength of only 100 Jy. The level of equipment sophistication required to detect these sources will therefore vary considerably – from a standard communications receiver to detect solar bursts, to special temperature controlled receivers and preamplifiers to detect external galaxies.

Almost all amateurs begin by detecting the Sun. This is easy to do, especially in the middle of the Sun spot cycle where there are many solar storms and bursts. The next goal might be to detect Jupiter or a quiet Sun, followed by a supernova remnant such as Cassiopeia. With this level of sensitivity it is then possible to make maps of radio noise in the Milky Way and to detect and plot the distribution of the neutral Hydrogen emission line at 1420.4MHz.

2.2 Spectra of radio sources

There are three main types of astronomical radio emission mechanism:

- Thermal noise
- Non-thermal e.g. synchrotron generation
- Line emissions from atoms and molecules

Each of these mechanisms produces a different spectrum of radiation and in a real measurement they will all be present to some extent. The task of the radio astronomer is to separate out the different spectra that make up the observed spectrum in order to determine the physical generation mechanism - or mechanisms – that are taking place in the region of space being observed. This is how knowledge of some of the physics behind the observed Universe is uncovered.

2.2.1 Thermal noise

Solid objects at some temperature T, radiate a continuum of electromagnetic radiation due to the vibration of the constituents of atoms and molecules. There are very few free electrons, and displacements are small, resulting in low levels of emission. For objects at a few hundred degrees Kelvin most of the radiation is at infra red wavelengths. The hotter the object becomes the wavelength of the peak emission of the radiation decreases toward the optical – the object becomes ‘red or yellow hot’.

The emission spectrum of a perfect hot ‘black body’ was derived theoretically in 1901 by the famous physicist Max Plank and is shown in Figure 2.2.

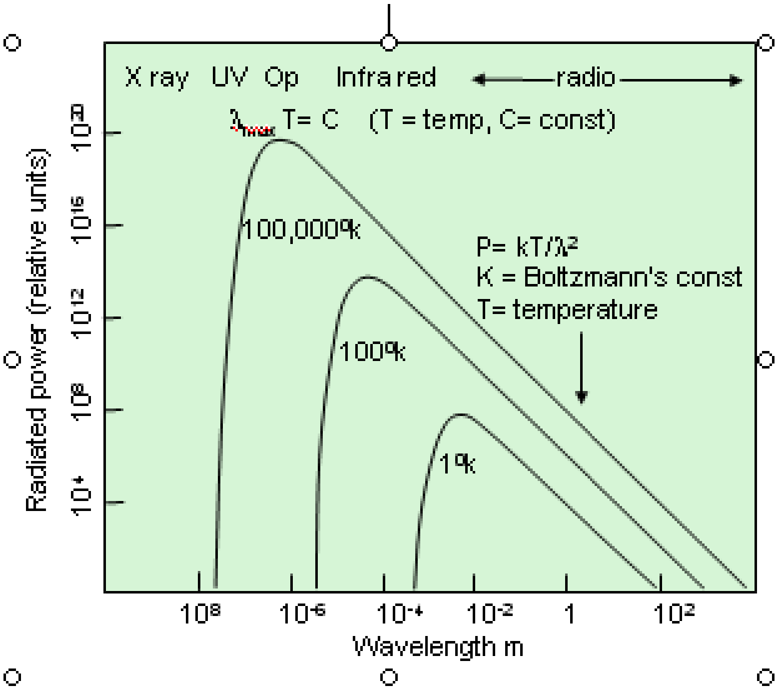


Figure 2.2 Black body spectrum

It can be seen that as the temperature increases, the wavelength of the peak emission decreases. For wavelengths much longer than λ_{max} the power of the emissions fall according to the Rayleigh-Jeans law P= kT/λ^2 .

A gas heated to a high temperature can emit more radiation as the particles move with greater speed. Ultimately, the gas atoms break up into charged ions and free electrons - a so called plasma. See Figure 2.3. Under these conditions the gas can radiate a significant amount of electromagnetic energy across a broad spectrum. In radio astronomy we do detect thermal emissions from cool solid objects such as the moon, but more often from regions of ionised gas such as in nebulae or around stars.

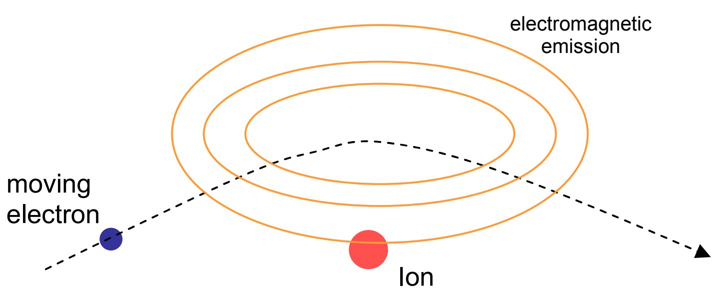


Figure 2,3 Emission from an accelerating electron

In this figure the electron is deflected (accelerated|) by the electric field of the ion and this causes it to emit radiation. The radiation may however be absorbed by other electrons and an energy balance between radiation and particles is achieved. With trillions of such encounters in a body of gas, all with random accelerations, a broad thermal noise spectrum is produced.

The radio emission spectrum of a dense excited gas (where self absorption occurs) can be described by the Rayleigh-Jeans law, but if the gas is tenuous - i.e. it is semi-transparent to the radio emissions – the equation must be modified to include a constant ε which depends on the self absorption of the gas. Thus we have:

$$P = \varepsilon\, kT/\lambda^2 \qquad \textit{equation 2.1}$$

For a dense opaque gas $\varepsilon = 1$ but in a semi-transparent gas (which is often observed in space) ε is proportional to λ^2, so the wavelength dependency in equation 2.1 falls out and the radiated power is constant.

This is shown in Figure 2.4 where the semi-transparent region is shown from x to y and the opaque region from y to z.

We know that the emission mechanism is thermal if this sort of spectrum is measured. It is also possible to determine something about the density of the gas cloud from its emission spectrum.

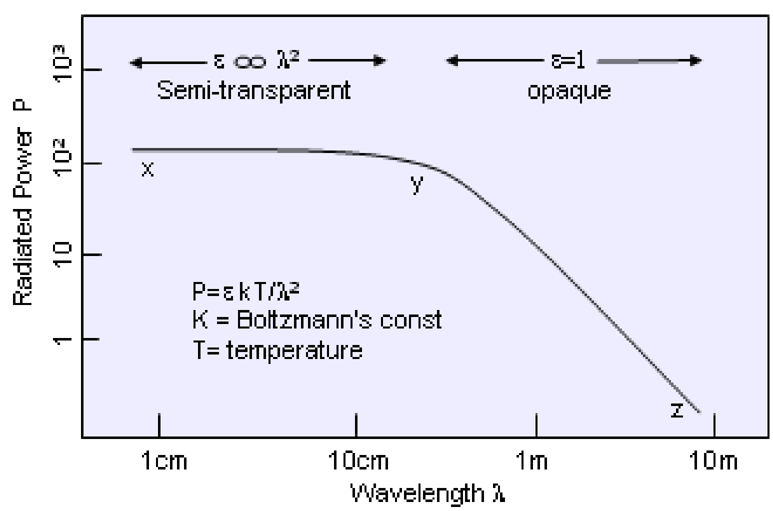


Figure 2.4 Thermal radio emission spectrum from a gas

2.2.2 Non-thermal radio emission

There are mechanisms that produce strong radio emissions that are not due to random thermal motions of electrons. The processes are more 'organised' and the agent is often a magnetic field. The emission spectrum produced has the opposite frequency dependence to thermal emissions. The radiated power increases with wavelength as shown in Figure 2.5.

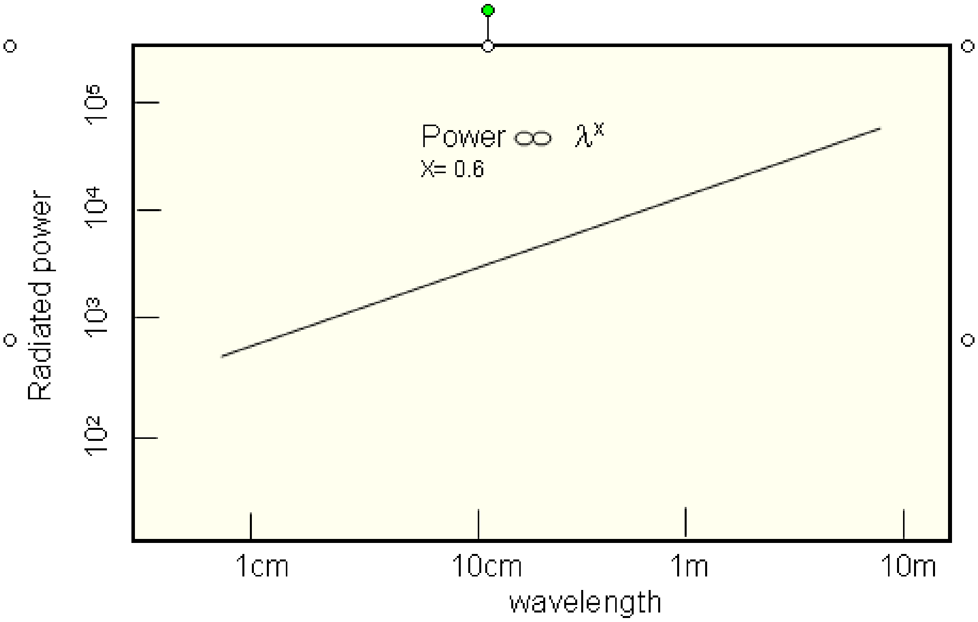


Figure 2.5 Typical spectrum of a non thermal source

Fast moving charged particles from very hot plasma or cosmic rays will interact with a magnetic field that may be present in the medium in a certain way. They will rotate around the field lines as shown in Figure 2.6 and as their direction is constantly changing, they are being accelerated – and thus they radiate electromagnetic energy.

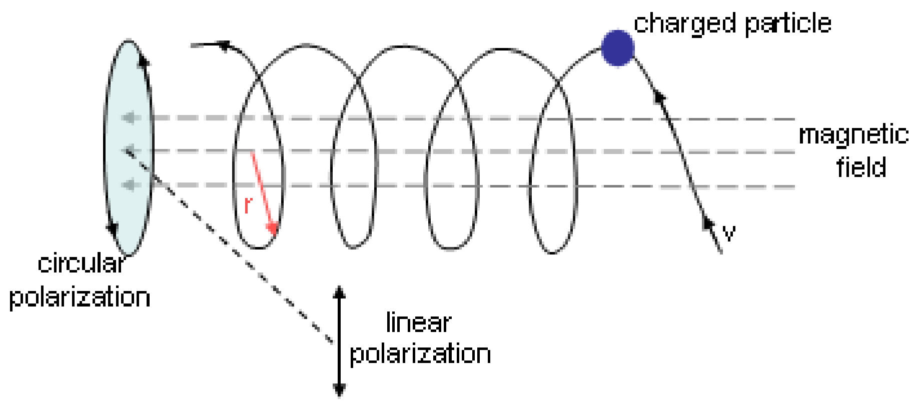


Figure 2.6 Charged particle in a magnetic field

When a charged particle moving with a velocity v encounters a magnetic field it will enter into a spiral orbit with a radius r around the field lines and radiate energy with circular polarization when looked at along the field lines. If viewed from normal to the field lines the polarization appears linear.

If, when observing a celestial source, we detect a polarized signal, this is clear indication of the presence of fast moving charged particles in a magnetic field.

When the velocity of the particle is much less than the speed of light the interaction is called a cyclotron process – and the radiation is called cyclotron radiation. When the velocity of the particle approaches the speed of light, as it does with cosmic rays or in plasma jets of neutron stars or black holes, relativistic physics becomes important and the cyclotron process becomes a synchrotron process as shown in Figure 2.7.

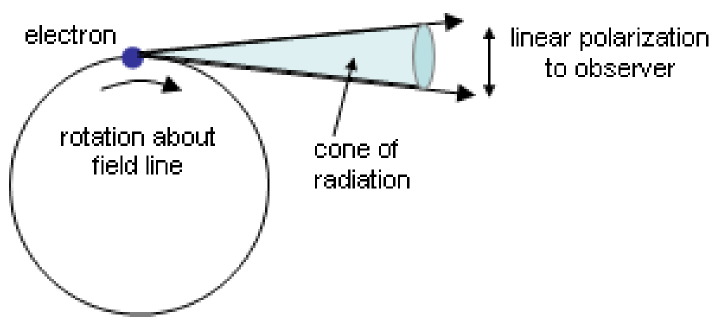


Figure 2.7 Relativistic electron – Synchrotron process

The inclusion of relativistic effects results in the radiation being beamed in a narrow cone away from the electron as it rotates about the field lines. This magnifies the power density of the radiation 'beamed' toward the observer. Many strong radio sources are generated by this mechanism as the electrons have such a large store of energy due to their high velocity.

The non-thermal spectrum from a synchrotron source is compared with that from a thermal source in Figure 2.8.

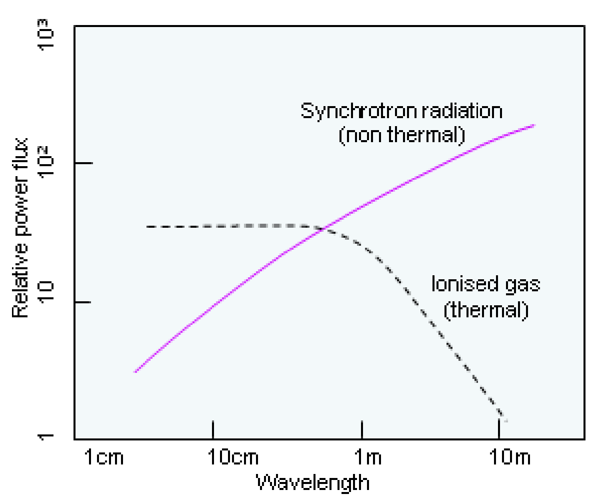


Figure 2.8 Synchrotron and thermal spectra

The spectra of many astronomical sources are non-thermal as can be seen in Figure 2.9.

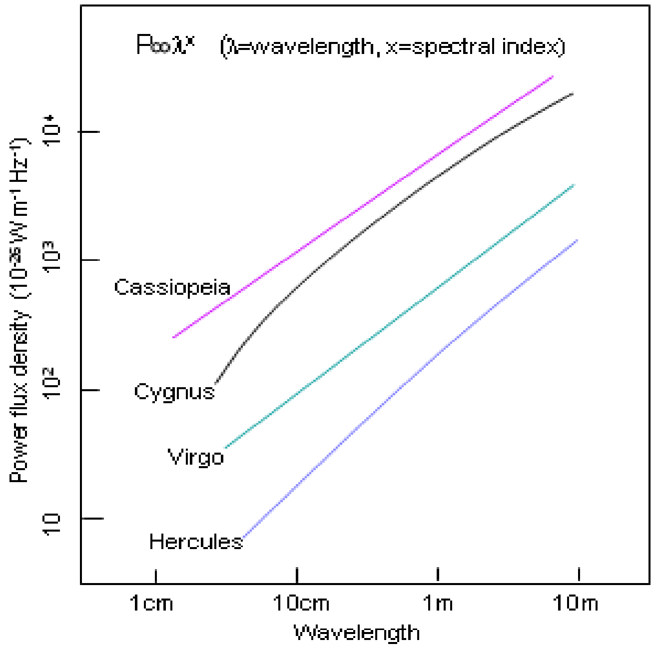


Figure 2.9 Non-thermal spectra of sources

2.2.3 Spectral line emissions

These narrow bandwidth emissions are created when the quantum state of an atom changes. It was shown by Plank and Bohr in the early 20th century that atoms absorb or emit energy in discrete steps called quanta. It was shown that:

$$E = h\nu \qquad \textit{equation 2.2}$$

Where E = quantum energy
h = Planks constant
ν = frequency

Consider the case shown in Figure 2.10 where a neutral hydrogen atom is shown in two quantum states. On the left the particle 'spins' are aligned – on the right they are opposed. There is a difference in energy between these two states and this manifests itself by the emission of radiation with a specific frequency ν_T (the transition frequency).

This is the frequency emitted by the 'spin transition' in the 'lowest energy state of the hydrogen atom - known as the 'ground state' - and occurs at 1420.4MHz , or ~ 21cm wavelength.

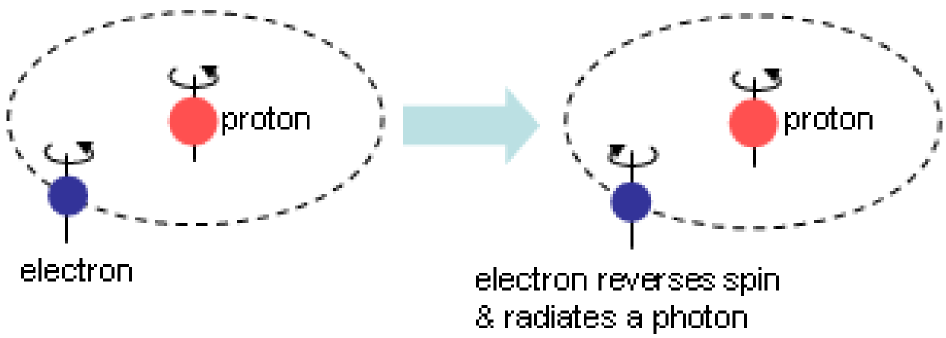


Figure 2.10 Spin transition in Hydrogen ground state

Many radio line emissions can be generated by atoms and molecules. The most common is Hydrogen, due to its abundance in the Universe, but OH, CO, H_2O and many other have been detected and mapped by modern professional radio telescopes. The frequencies of some of these emissions are given in Table 2.1.

Rest frequency of spectral lines

Atom/Molecule	Line Name	Rest frequency (GHZ)
HI	neutral hydrogen	1.420405752
OH	hydroxyl radical	1.6122310
OH	hydroxyl radical	1.6654018
OH	hydroxyl radical	1.6673590
OH	hydroxyl radical	1.7205300
H_2CO	ortho-formaldehyde	4.829660
CH_3OH	methanol	6.668518
HC_3N	cyanoacetylene	9.009833
CH_30H	methanol	12.178593
H_2CO	ortho-formaldehyde	14.488490
C_3H_2	ortho-cyclopropenylidene	18.434145
H_20	ortho-water	22.23507985
NH_3	para-ammonia	23.694506
NH_3	para-ammonia	23.722634
NH_3	ortho-ammonnia	23.870130

2.2.4 Summary

We have seen the key mechanisms by which radio sources emit signals. Each mechanism has its own spectral characteristics and will be found in different radio objects in space. By measuring the total emissions from a source and picking out the various spectral components much can learned about the physics of the region being studied.

We move now to a description of some individual radio sources and discuss how easy or difficult they are for detection and measurement by amateur radio astronomers.

3 The Sun

3.1 The Quiet Sun

The Sun is a relatively strong emitter of electromagnetic waves over a wide range of frequencies from metric, through infra red and optical to ultra violet and X rays. It is undoubtedly the brightest radio object in the sky and can be detected with modest equipment.

Many radio astronomers start by observing the Sun, especially when ‘Solar storms’ are occurring as the emissions produced are many orders of magnitude larger than those from a quiet or ‘quiescent’ Sun.

A typical spectrum of radio emissions under quiet conditions is given in Figure 3.1. We see that signal strength increases with frequency and decreases with wavelength. This is typical of a *thermal* source where the generation mechanism is due to thermal agitation of the gaseous material of which the Sun is composed.

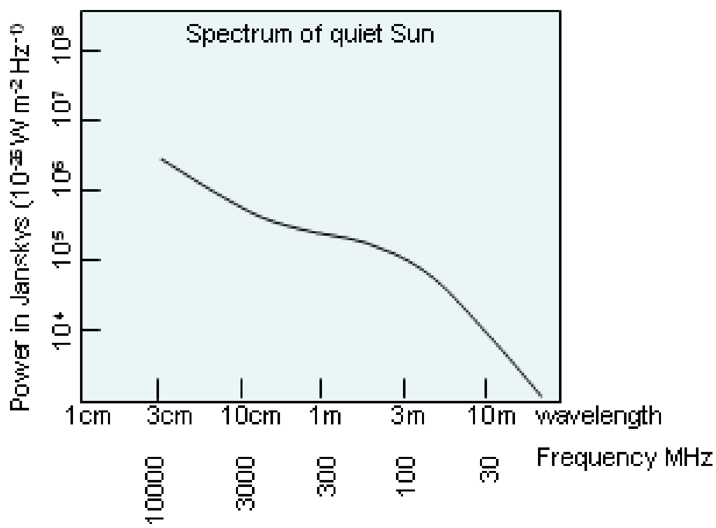


Figure 3.1 Radio spectrum of ‘quiet’ Sun

3.2 Solar storms

When significant sunspots occur, the radio output increases with sharp signal ‘spikes’ as shown in Figure 3.2 [1]

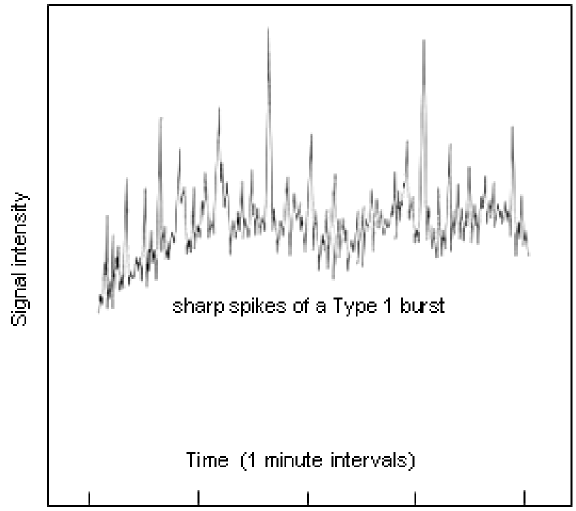


Figure 3.2 Type 1 solar bursts

The spectrum of storms and bursts is shown in Figure 3.3 and clearly suggests that the generation mechanism is non-thermal (the spectrum slopes the opposite way to the thermal emission from a quiet Sun). The waves from bursts are also strongly circularly polarized by the intense magnetic field associated with sun spots.

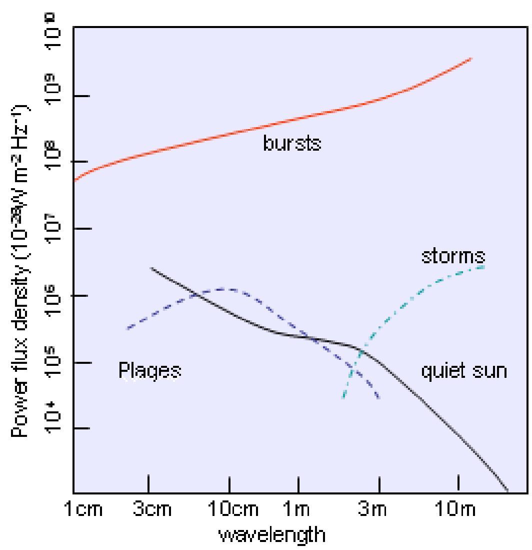


Figure 3.3 Spectra of Solar emissions

There are other outbursts from the Sun. Type 2 are found to drift from high to low frequencies with a rate of about 1MHz/ second, are randomly polarized and are believed to be produced by plasma oscillations. Type 3 emissions are sometimes called 'fast drift' bursts because the change frequency is at around 20MHz/ second. Occasionally after a large solar flare there is a long burst of wideband radiation from metres to low microwaves – these are called Type 4 emissions. See Figure 3.4 [2].

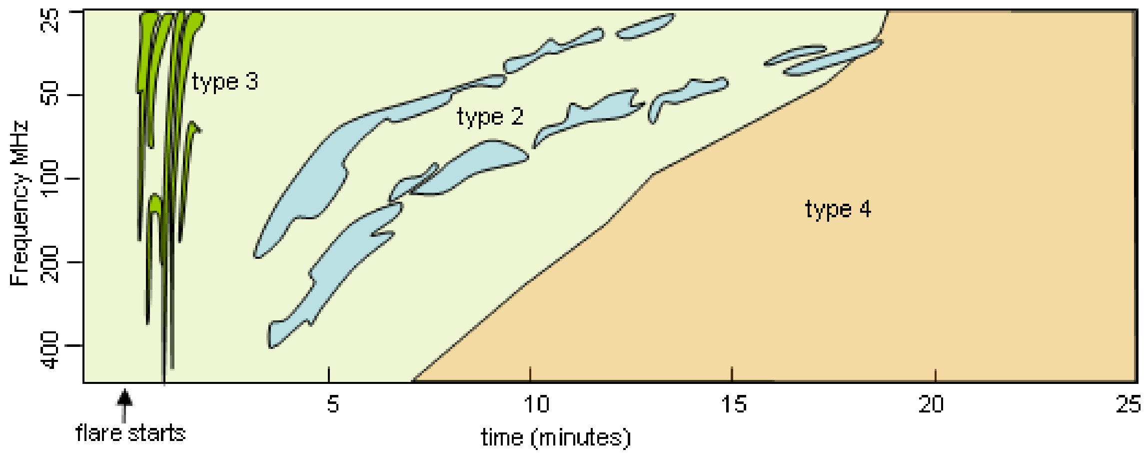


Figure 3.4 Dynamic behaviour of Solar emissions

Plages - radio bright areas of the sun associated with regions of sunspot activity.

Figure 3.5 shows an enormous solar eruption that occurred in October 2003 – note the size of the plasma ejection compared to the Earth.

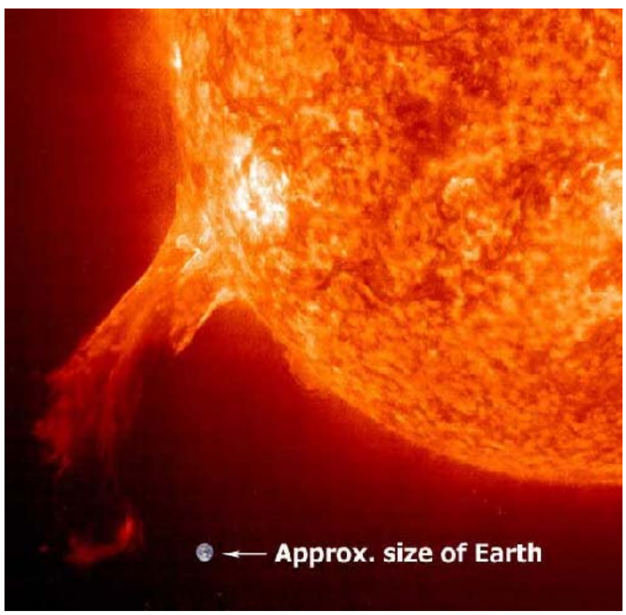


Figure 3.5 A Solar eruption

There is much that can be studied on the Sun by measuring the radio output at a number of frequencies that can be received with a general purpose communications receiver and a few types of antenna designed for the HF and VHF bands. Amateur radio astronomers can start by setting up such equipment and monitoring the Sun over long periods of time to establish trends and sudden events such as solar storms.

4 Jupiter

4.1 Detection of Jupiter signals

From Figure 2.1 we can see that the signal levels on Earth from Jupiter are about 10^5 Jy which is comparable to the quiet Sun and low level solar storms. The same equipment used to detect solar emissions can be used to receive signals from Jupiter. Greater attention has to be paid the design and positioning of a suitable HF antenna that has some directionality [3, 4]. A wire dipole 22 feet long set between 0.25 and 0.5 wavelengths above the ground will produce a beam at 21MHz such as is shown in Figure 4.1. If this antenna is connected to a communications receiver when Jupiter is positioned to be in the beam, a variety of noisy signals may be heard. These vary considerably and are related to the position of the moon Io. There are many web-sites dedicated to observations of the complex emissions from Jupiter [5,6,7] and one should look at these for details of emission classifications and technical details of equipment.

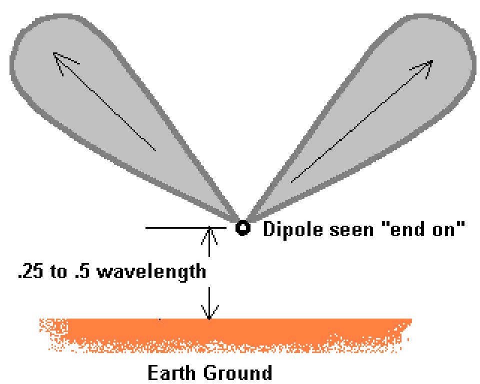


Figure 4.1 Dipole antenna pattern for detection of Jupiter noise

There are three major factors not related to observing conditions on Earth which have been identified to affect the probability of hearing Jupiter's decametric emissions at any given time [8] :

- The central meridian longitude of Jupiter that faces us.
- The position of the innermost moon Io in its orbit around Jupiter
- The Jovicentric declination of the Earth

An illustration of the Jovian radiation belts and the spiral motion of trapped electrons is given in Figure 4.2,

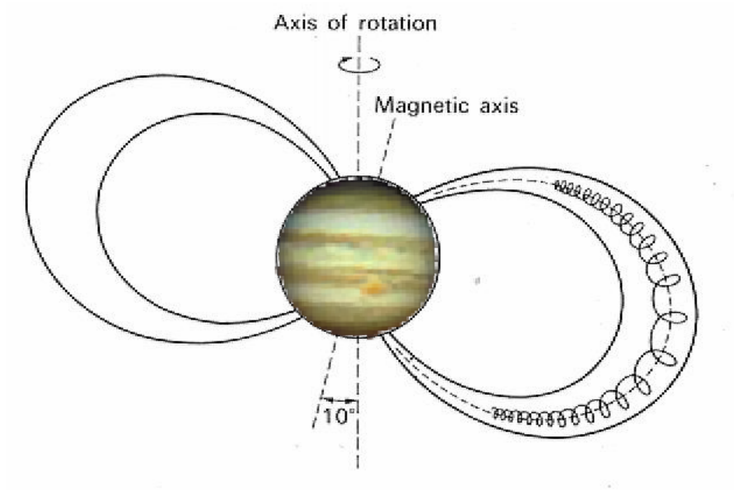


Figure 4.2 Jovian magnetosphere

Some patience is required to detect the radio emissions from Jupiter as conditions are not always favourable and long observing sessions are sometimes needed.

4.2 Spectrum of Jupiter emissions

Signals from Jupiter were first detected in 1958 at a wavelength of ~3cm, but it was not until measurements were made in the HF band that it was realised how strong the emissions were. The spectrum is complex and is composed of two parts as shown in Figure 4.2.

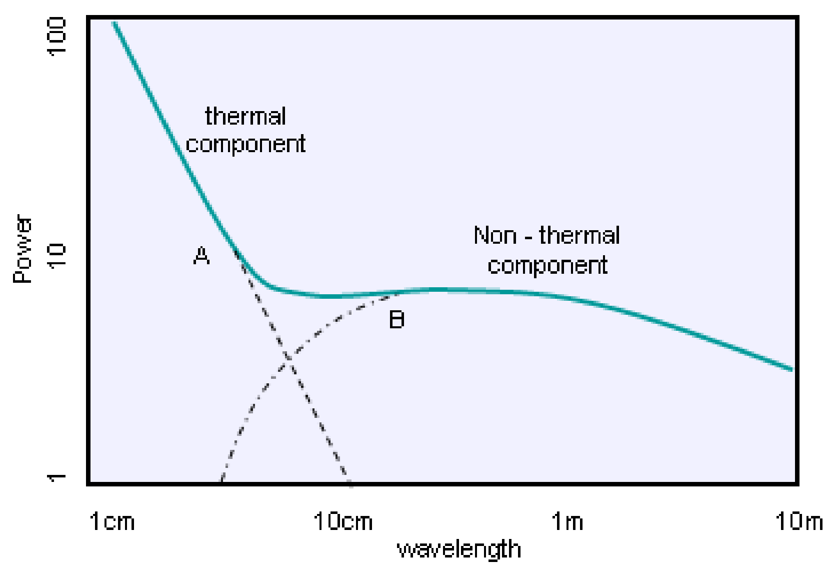


Figure 4.2 Complex spectrum of Jupiter emissions

The thermal component A arises from the cold planet and its atmosphere at a temperature of 130^0 K. The intensity of the non-thermal component B is much greater at wavelengths longer than 10cm and is generated by the interaction of high energy electrons (~10MeV) with the planet's magnetic field that has a strength of about 1 gauss. A centimetric emission map of the active region is shown in Figure 4.3.

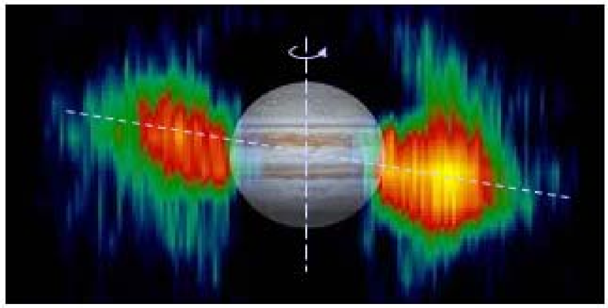


Figure 4.3 Radio emission map at centimetre wavelengths

Jupiter is a good 'target object' for the amateur radio astronomer with fairly basic equipment, however a large antenna is required and this can be difficult to erect in a limited space and in the midst of interfering electronic equipment in urban situations.

5 The Moon

The moon is a solid body with no significant atmosphere; it therefore radiates as a cool solid body (thermal radiation) and is not easy to detect at long wavelengths. It is possible for the amateur to make observations with access to an old C band (4 – 8 GHz) satellite TV antenna with a diameter of a few metres as shown in Figure 5.1.

The typical beam width of a 3m diameter dish at 4GHz is ~ 2^0 – rather larger than the angular diameter of the moon at 0.5^0. The moon will therefore present almost a point source to the antenna and a transit scan across the moon will produce a trace with the properties of the antenna beam: i.e. a detection that is about 2^0 across. However it is still an interesting exercise to attempt to detect a cold, purely thermal radiating body.

Figure 5.1
3m dish with C band feed

The moon has no significant magnetic field and no ionised gaseous atmosphere containing free electrons, so there is no mechanism to generate non-thermal radio emissions. The thermal signal from the Moon is quite low and a fairly good receiver is needed to make a successful detection.

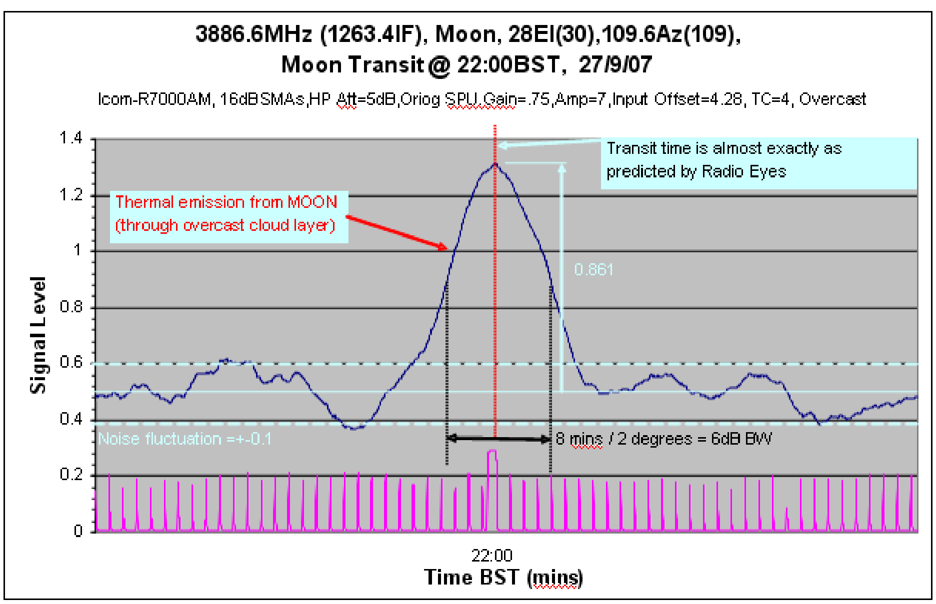


Figure 5.3 Detection of thermal emission from the Moon

6 Galactic Hydrogen Line

6.1 Emissions outside the Solar System

Having examined the emissions from bodies within the solar system, we now look much further out into the Milky Way. The most abundant element in the Universe is Hydrogen and it exists in atomic and ionised forms in large amounts within our galaxy. As discussed in section 2.2.3, atomic hydrogen can emit a specific spectral line at 1420MHz. By measuring the strength of this 'line emission' it is quite possible for the amateur radio astronomer to map the hydrogen distribution in part of our galaxy.

In order to do this, the observer needs good antenna and receiver equipment that is stable over hours and days of observing time. This usually requires the sensitive receiver elements to be temperature controlled to avoid drifts in noise level and receiver gain.

Assuming this can be done, an amateur observer can produce a map such as that shown in Figure 6.1. by measuring the signal strength as a function of transit time at a number of declinations on different days and combining the data with computer software tools.

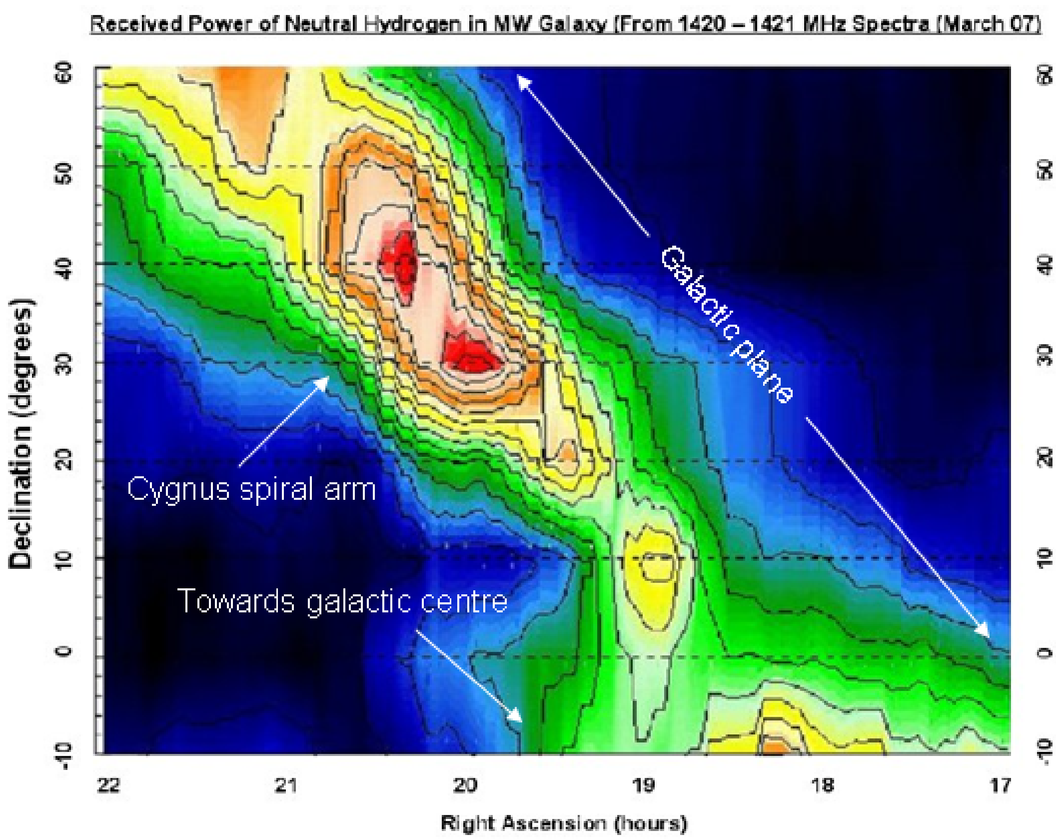


Figure 6.1 Map of atomic Hydrogen in the galactic plane

6.2 Galactic distribution of Hydrogen

The narrow spectral line emission from Hydrogen is Doppler shifted by the relative line-of-sight velocity of the source region to the observer. This provides a way for professional radio astronomers to separate out the signals from different spiral arms of the galaxy, that each have different relative velocities. By this means it is possible to plot the density of Hydrogen (related to signal strength) to the location of the source position (related to the Doppler shift) and generate a ‘top down’ view of the spiral nature of the galaxy from measurements made from the Earth, which of course lies within the galactic plane.

This cannot be done optically as dust in the galactic plane largely obscures the spiral arms.

In Figure 6.2 we see a ‘top down’ map of the galaxy produced in 1964. The sector marked in blue is that related to the amateur map in Figure 6.1 The dark sectors along the 0^0 to 180^0 line of galactic longitude is blank because there is insufficient Doppler shift for the calculations to be made.

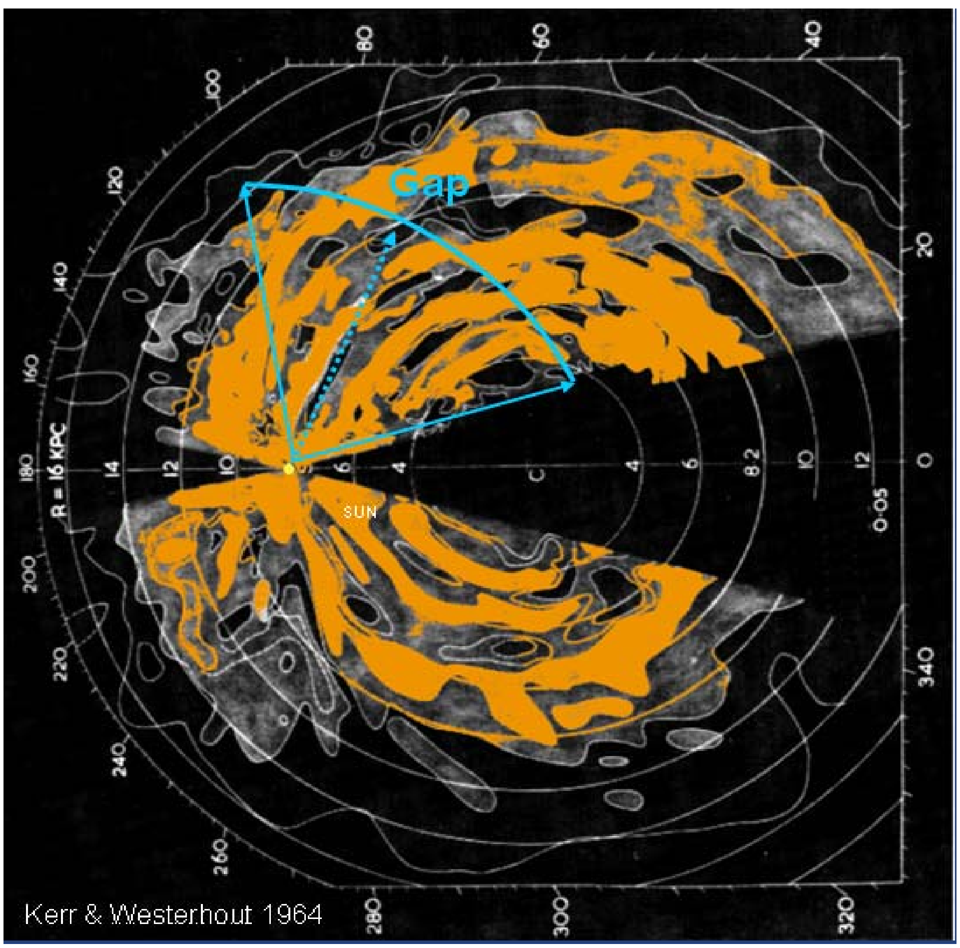


Figure 6.2 Hydrogen distribution in the Milky Way

7 Galactic continuum emissions

7.1 Constituents of continuum emissions

Very broadband continuous radio emissions are referred to as 'continuum' emissions and are composed of two main types:

- Thermal emissions
- Cyclotron / synchrotron emissions

The generation mechanisms for both types were discussed in section 2. In this section we look at continuum emissions that can be observed by amateur radio astronomers.

Because of the different spectra, emissions from either type will tend to dominate in certain frequency bands. Thermal emission is more easily detected at high frequencies above a few GHz, whereas synchrotron emission increases with decreasing frequency as is more easily detected at low frequencies in the HF to UHF bands.

It follows that observers should construct equipment that is capable of operation in either frequency regime depending on what type of continuum emission they seek to measure.

7.2 Synchrotron emissions

We will give an example of thermal emission from nebulae later in this paper but here we will examine how the amateur radio astronomer can plot the distribution of synchrotron emission in the Milky Way.

If equipment has been designed to detect the neutral Hydrogen line at 1420MHz it is convenient to use frequencies close to this to observe synchrotron emissions. Because the line emission of Hydrogen is narrow (<1MHz) we can tune the receiver to a frequency close by and detect only the broad band synchrotron signal. In the example that follows, the chosen frequency was 1453MHz – which was far enough away from the Hydrogen line, but still within the bandwidth of the antenna and receiving equipment.

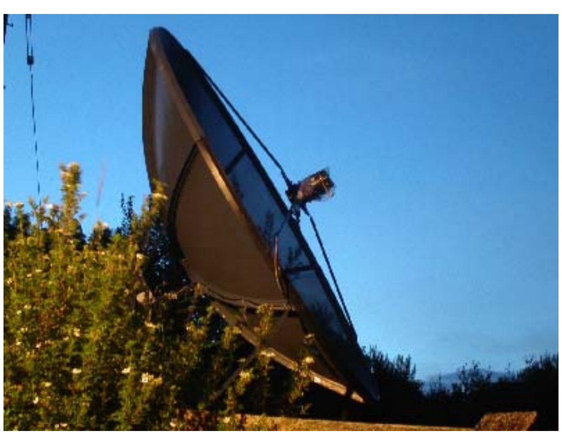


Figure 7.1
3m dish with
1400 -1500MHz
feed

By setting the antenna at a series of declinations over a period of several days, a succession of transit scans through the galaxy can be made resulting in a set of plots as shown in Figure 7.2.

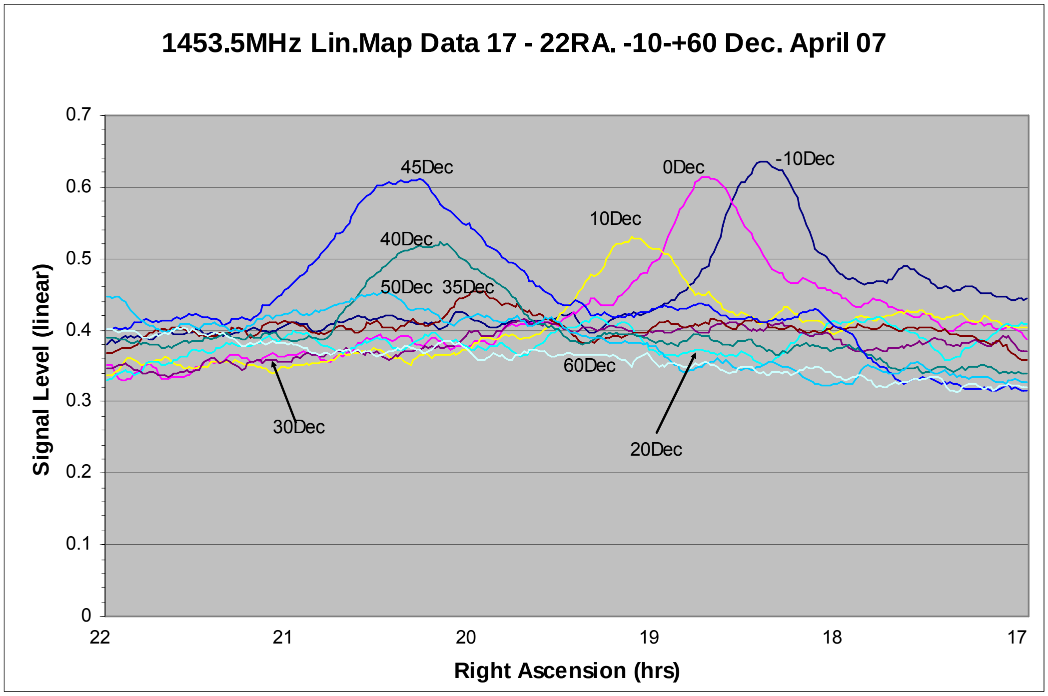


Figure 7.2 Transit scan data (synchrotron emissions)

The data can be assembled as a 'false colour' map using suitable software[9] as shown in Figure 7.3.

In this diagram we see the radio map at 1453.5MHz converted to galactic coordinates[12] and superimposed on an optical picture of the Milky Way. There are several interesting things to note about this map:

- The low signal level of the emission at galactic longitude of 60^0 corresponds to the gap seen between spiral arms in Figure 6.2. The antenna is pointed in a direction where there is low concentration of matter and plasma and the integrated signal along the line of sight is low. This also shows up on the optical image where the region is largely dark.
- Closer to the centre of the galaxy at a longitude of ~35^0 there is an excursion on the radio map known as the North Galactic Spur, thought to be part of the giant arc of an ancient supernova remnant. There is no optical counterpart to this feature.
- The radio and optical emissions peak again at a galactic longitude of 80^0 where we are looking along the Cygnus spiral arm and the integrated radio and optical emissions are bright.

As has been shown, detecting the galactic synchrotron emission is a credible project for the amateur radio astronomer

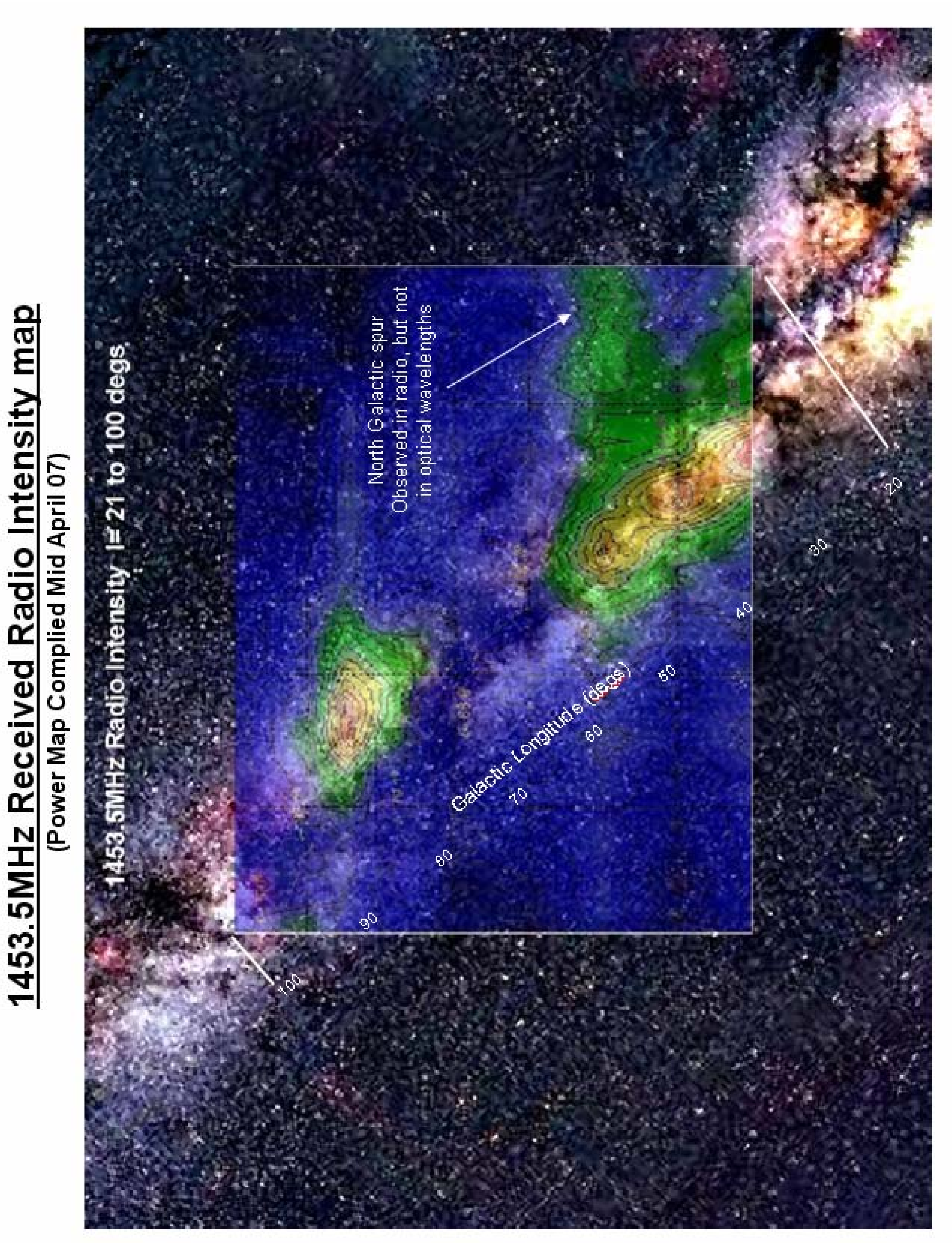


Figure 7.3 Map of galactic radio synchrotron emission

8 Supernova Remnants

Supernova remnants are vast almost spherical shells of plasma moving with extremely high velocity into space as a result of high mass stellar explosion. The plasma moves – and carries with it – a significant magnetic field with which the plasma interacts to produce strong synchrotron emissions. As the relativistic plasma shock wave slams into the surrounding tenuous interstellar material further emissions are generated.

There are a number of well known supernova remnants in our galaxy, some of which make good observing 'targets' for the amateur radio astronomer.

Name	Light reached Earth	Distance Ly
Cassiopeia A	17th C	10,000
Crab Nebula SN1054	1054 AD	6,300
Tycho's SN1572	1572AD	7,500
Sagittarius A (E)	?	26,000
Veil Nebula	>3600BC	1,400 – 2,600
Kepler's SN1604	1604	20,000
Vela SNR	11th – 9th Millennium BC	800

Some of these sources are too difficult for the amateur to observe: either they are too weak or at too low a declination for observers in the UK. For example, Sagittarius A cannot be observed from the southern UK as it lies too close to the horizon, and ground noise will enter the antenna beam and mask the source. The easiest supernova remnants to detect are Cassiopeia A (Right Ascension: 23:23:21 & Declination: 58:49:59) and Taurus A – the Crab Nebula (Right Ascension: 05:34:30 & Declination: 22:00:57). Unfortunately they both lie close to the galactic plane and this can make it difficult to separate them out from the integrated galactic emissions. See Figures 8.1 and 8.2 [11].

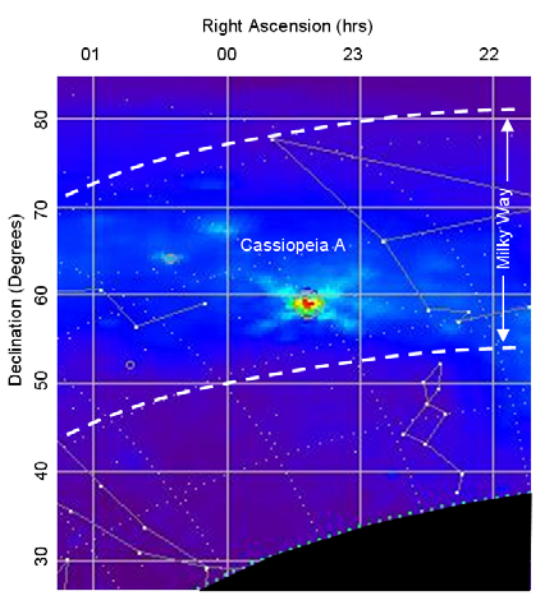


Figure 8.1 Location of Cassiopeia A

Cassiopeia A (3C461) lies in the outer edge of the galactic plane as seen from Earth. It is a very strong source at many wavelengths. In this picture from Radio Eyes [11] its intensity at 408MHz is given as 5500Jy.

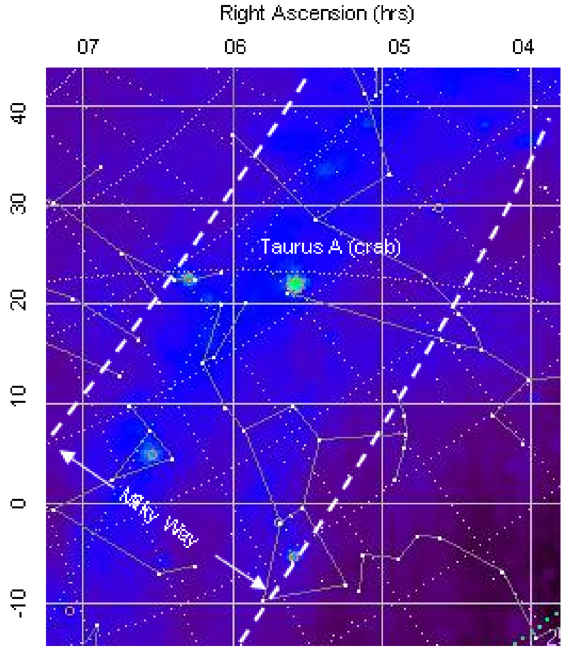


Figure 8.2 Location of Taurus A (Crab Nebula)

Taurus A (3C144) also lies in the outer galactic plane and has an intensity at 408MHz of around 1200Jy.

A good way to separate out point-like supernova remnant sources from the galactic background is to use a radio interferometer which will produce 'fringes' from the point source, but not from the widespread background. An example may be seen in Figure 8.3.

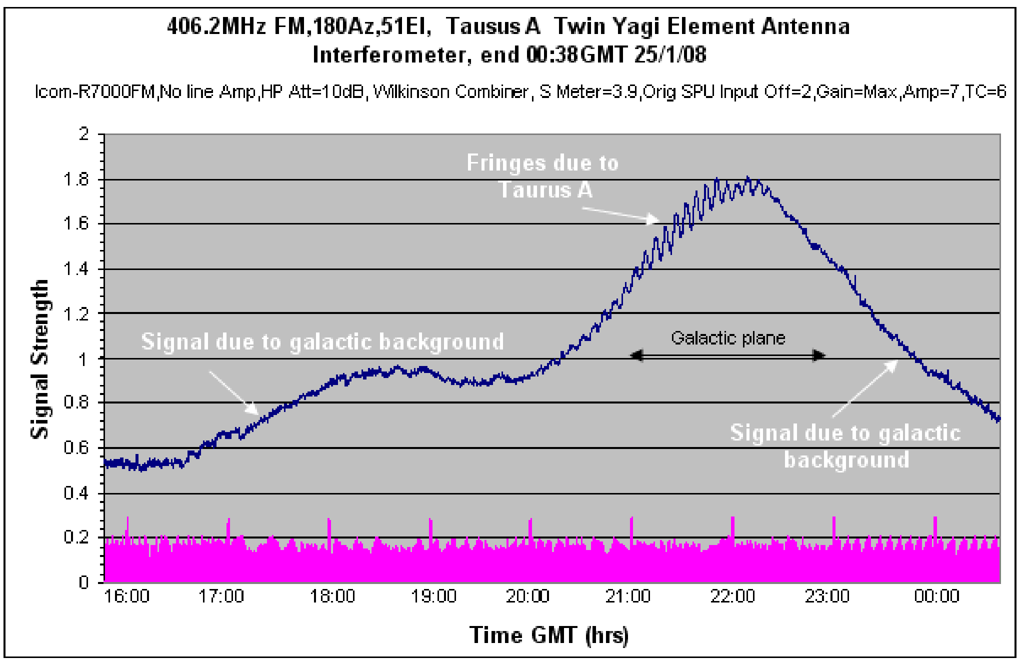


Figure 8.3 Separation of Taurus A from galactic background

Note that the 'hump' on which the fringes sit is due to the background emissions from the galactic plane. The fringes can easily be separated out with software as shown in Figure 8.4.

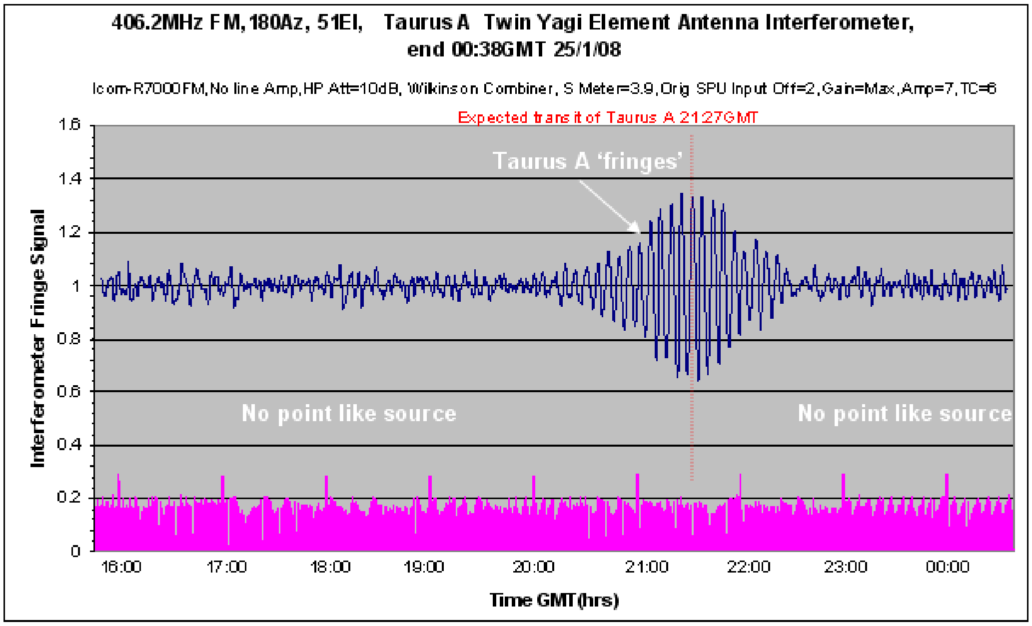


Figure 8.4 Amateur detection of the Crab Nebula

The Crab nebula supernova remnant is a beautiful visual and radio object - See Figures 8.5 & 8.6.

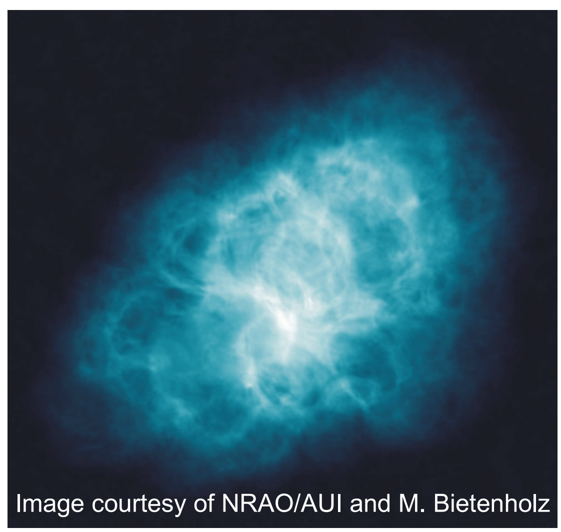


Figure 8.5 Crab Nebula (optical)

Figure 8.6 Crab Nebula Radio @ 5GHz

The remains of the original star has collapsed to a Neutron star and is a Pulsar spinning at 30 times at second and emitting its own special radiation pattern, but at levels much below that of the whole supernova remnant. Pulsars will be discussed in section 10.

9 Thermal Emission Nebulae

There are many emission nebulae where vast clouds of hydrogen are ionised by hot O and B type stars forming within them. The intense UV radiation from the stars ionises the gas at temperatures of around 10,000^{0}K and this causes the clouds to emit broad spectrum or 'continuum' radiation with thermal spectral characteristics as described in section 2.2.1.

One of the best examples of a thermal emission nebula is the Orion nebula depicted in Figure 9.1.

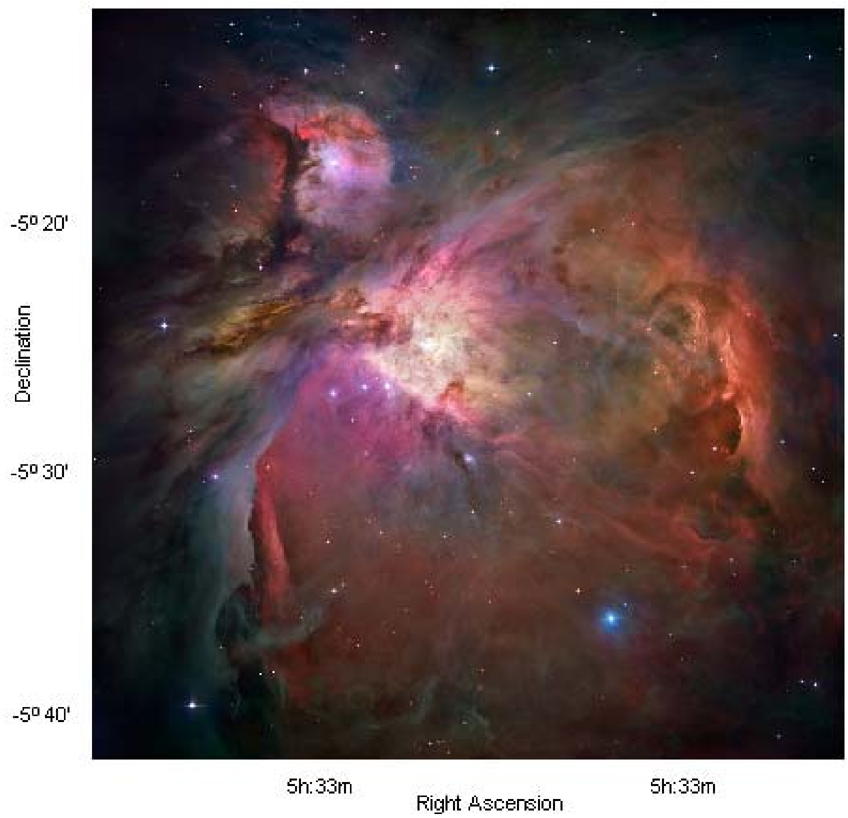
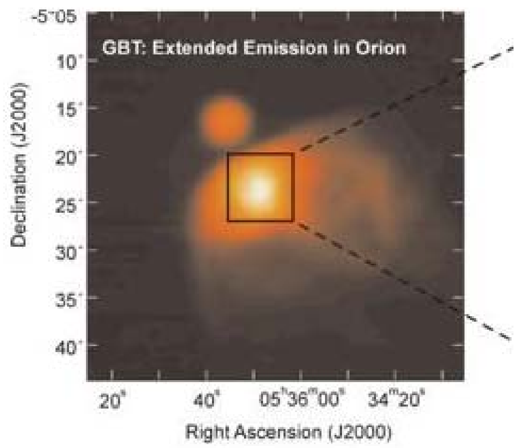


Figure 9.1 The Orion Nebula (HST picture)

The whole nebula is about 0.5^0 across [1] and the ionisation energy comes from the Trapezium cluster of bright stars containing two O stars and several B stars. There is also a large amount of obscuring gas and dust which is clear in the optical image.

The professional radio image from the NARO / AUI telescopes in Figure 9.2 a & b was generated at a frequency of 8.4GHz (3.6cm). Figure 9.2a is centred on RA: 05:35:17.40, Dec: -5:23:28.00 and has a field of view of 0.66^0 square. It shows the hydrogen nebula without the obscuring dust as this is transparent at GHz frequencies.



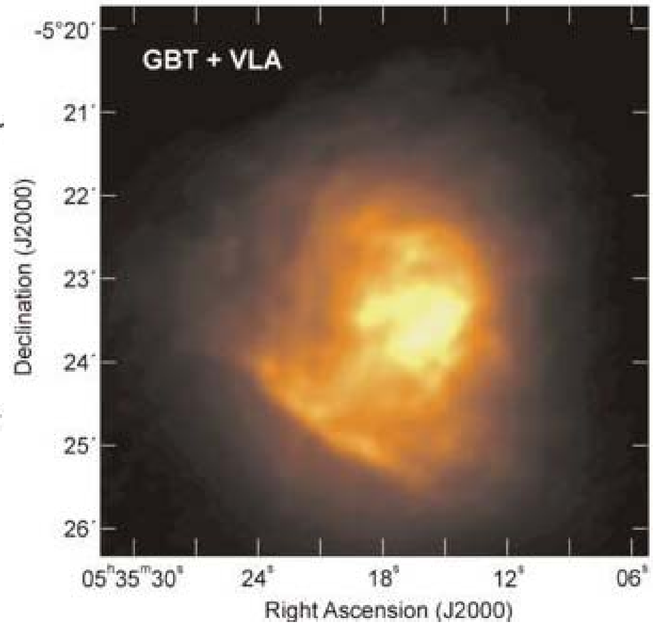


Figure 9.2 a   Orion nebula @ 8.4GHz

Figure 9.2b   Central region of nebula

The thermal emission spectrum of the nebula is shown in Figure 9.3 where the measured values agree with a theoretical prediction based an electron temperature of 10,000^{0}K. It is clear that the amateur radio astronomer would have the best chance of detecting the Orion nebula at wavelengths around 10cm or smaller. A C band satellite TV antenna and feed, such as that shown in Figure 5.1 could be used to make observations at around 4 GHz (7.5cm). The expected signal strength would be of the order of 500Jy.

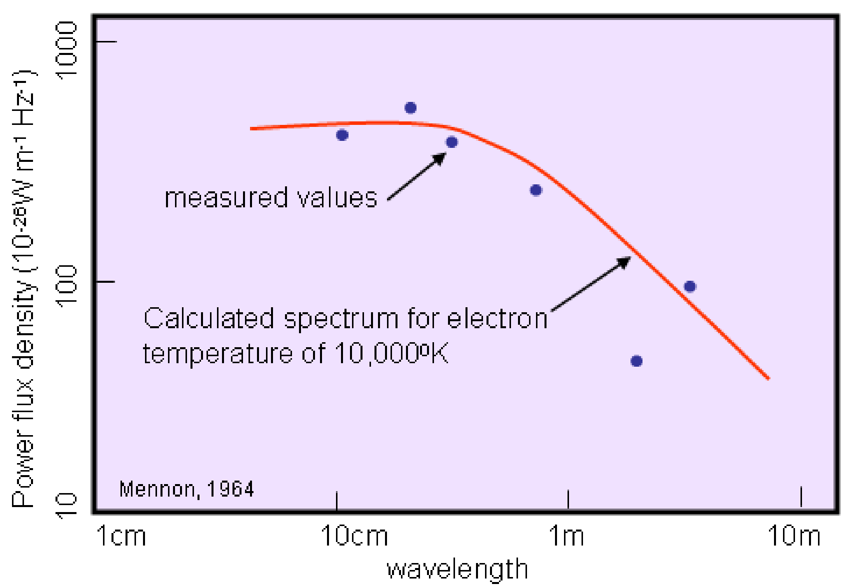


Figure 9.3   Thermal spectrum of the Orion nebula

10 Pulsars

10.1 The nature of Pulsars

Pulsars are compact sources that emit a series of fast radio pulses. They are in fact neutron stars about 20 km in diameter and have a mass of about 1.4 times that of our Sun. This means that a neutron star is so dense that on Earth, one teaspoonful would weigh a billion tons. Because of its small size and high density, a neutron star possesses a surface gravitational field about 2×10^{11} times that of Earth. They can also have magnetic fields a million times stronger than the strongest magnetic fields produced on Earth [12].

Pulsars were first discovered in late 1967 by graduate student Jocelyn Bell Burnell, as radio sources that blink on and off at a constant frequency. Now we observe the brightest ones at almost every wavelength. Pulsars are spinning neutron stars that have jets of particles moving almost at the speed of light streaming out above their magnetic poles.

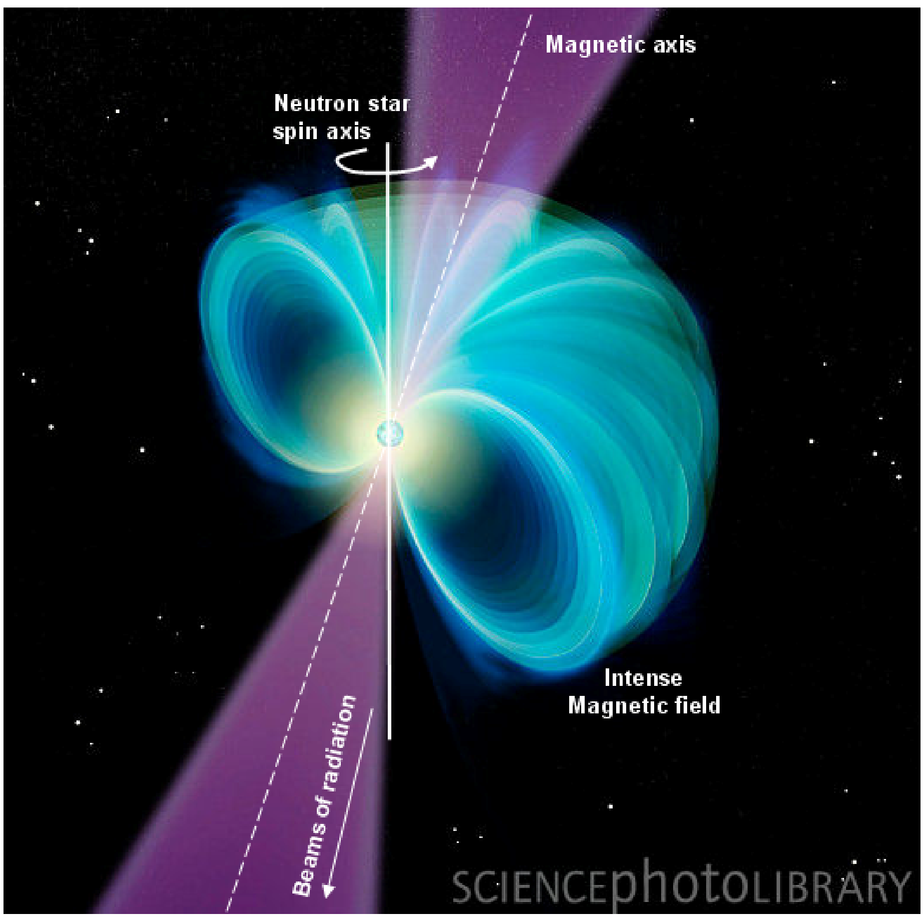


Figure 10.1 A Pulsar - A spinning Neutron Star

In Figure 10.1 we see a compact stellar remnant spinning about its axis of rotation with an intense magnetic field (created as the star collapsed) at some angle to the spin axis. The intense beams of radiation emerging from the magnetic poles sweep around in space like a light-house beam. Each time the beam crosses an observer's location he sees a short intense radio pulse which has the regular period of the Neutron star's rotation. A typical pulse train is shown in Figure 10.2 [13].

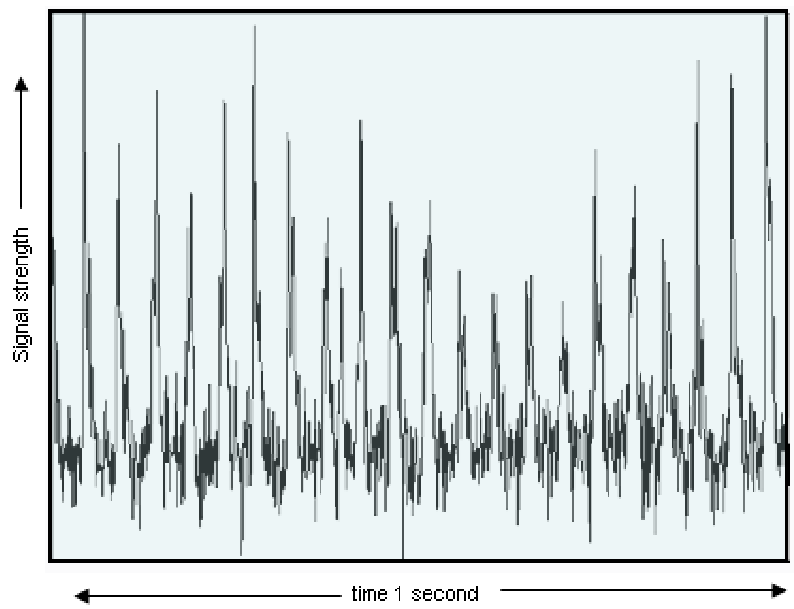


Figure 10.2 Pulsar signal

10.2 Observing Pulsars

There are two characteristics of pulsar signals that make observing them different from all the 'noise like' emissions discussed earlier:

- The signals are low level ~ 1Jy or less
- The signal level pulses with a repetition rate of up to 30Hz

The low signal level requires a large aperture antenna and very low noise receiver whilst the pulsed nature of the signal means that the observer cannot use signal integration over a period of many seconds to reduce signal variability. Integration would destroy the pulse structure of the signal.

These features make pulsar observations almost the ultimate challenge for the amateur radio astronomer with limited equipment. Some observers [14,15] using a modest 10 foot diameter dish claim to have observed a number of pulsars with the aid of special post detector software which enhances the pulse structure within background noise.

There is still a deal of work going on by professional radio astronomers to understand the emission generation mechanisms in pulsars. There is a wide variety of pulse rates, emission spectra and source intensities for which a full explanation is currently being sought.

For amateur radio astronomers, simply detecting a pulsar would be an achievement of some note.

Indeed, one of the members of the Society of Amateur Radio Astronomers (SARA)[16] Jim Van Prooyen[17] has made great efforts to detect pulsars with a 10 foot diameter dish – and larger antennas - by developing special software to recover pulses from a noisy signal.

He comments that - "There have been several efforts by amateur radio astronomers to build [pulsar detectors], and for some of us, the detection of pulsars is the *Quest for the Holy Grail* of amateur radio astronomy. There are a number of notable efforts:

- James C. Carroll (A Post Detector Pulsar Extractor – SARA Paper)
- Robert M. Sickels (Pulse Catcher – SARA Paper)."

Van Prooyen has published the graph in Figure 10.3 showing the detection of Pulsar B0031-07 which he made using his post detector software capability.

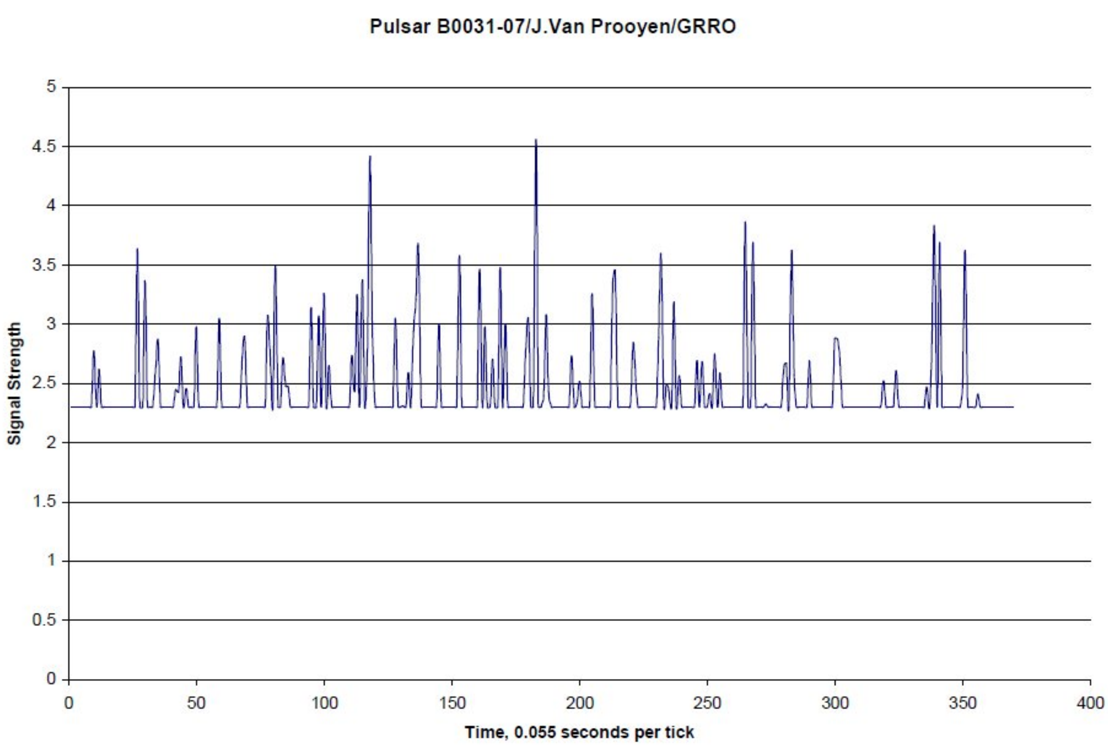


Figure 10.3 Amateur detection of Pulsar (Van Prooyen)

10.3 Pulsar emission spectra

A great deal of work has been carried out by professional radio astronomers to determine the nature of the emission spectra from a large variety of pulsars. In general they follow the simple synchrotron shape as given in Figure 2.5, A spectrum of Pulsar B1557-50 is shown in Figure 10.4.

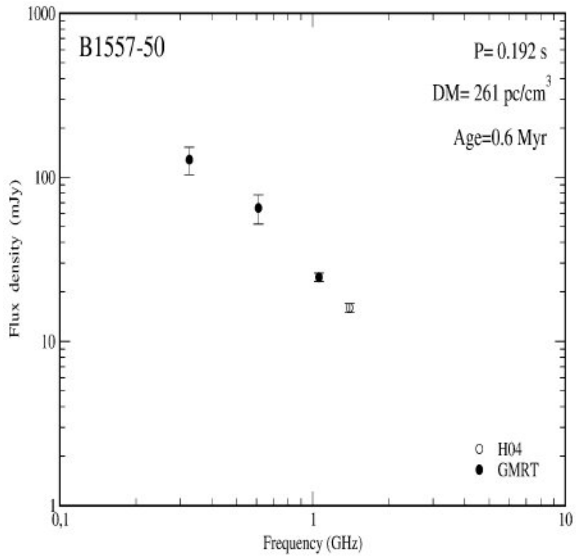


Figure 10.4 Simple Pulsar spectrum

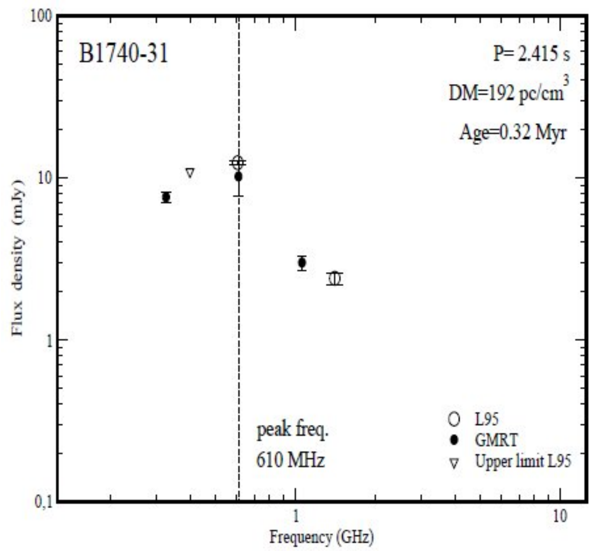


Figure 10.5 'turn over' pulsar spectrum

However evidence has been found of a 'turn over point' where the emission is a maximum – falling away on either side as shown in the example in Figure 10.5 for Pulsar B1740-31.[18] This suggests that a useful frequency to observe is in the UHF band (300MHz up to about 1GHz).

Note that the power flux density for these Pulsars is in the milli-Jansky range (mJy). A big challenge for amateur observers!

11 Extra-Galactic sources

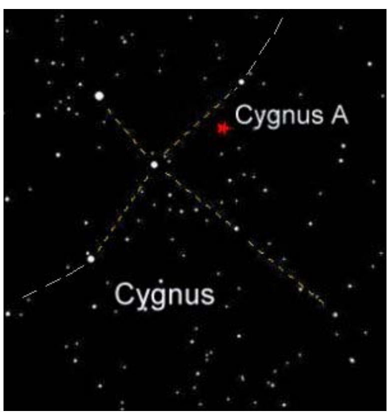
11.1 There are a few extra-galactic sources that can be observed by amateurs. Two will be highlighted in this section – one is a strong source that is easily detected, the other is something of a challenge.

- The strong source is Cygnus A (3C405)
  RA 19^h 59^m 28.3566^s DEC +40° 44′ 02.096″

- The weaker source is Virgo A M87 NGC 4486
  RA 12^h 30^m 49.42338 DEC +12° 23′ 28.0439″

Cygnus A (3C 405) is one of the most famous radio galaxies, and among the strongest radio sources in the sky. It was discovered by Grote Reber in 1939. In 1951, Cygnus A, along with Cassiopeia A, and Puppis A were the first "radio stars" identified with an optical source; of these, Cygnus A became the first radio galaxy.[19]

11.2 Cygnus A
The radio source can be located as shown in Figure 11.1. It is a peculiar-looking, 15th magnitude galaxy located in the constellation Cygnus which would probably never have come under scrutiny were it not for the fact that it is the host for one of the strongest radio sources in the sky [20].



Located 600 million light years away, this galaxy is among the giants of the universe with a mass estimated at 100 trillion times the sun's mass. It consists, apparently, of two nuclei separated by 5500 light years, embedded in a galaxy extending some 450,000 light years across. The two nuclei of Cygnus-A are probably all that remain of two separate galaxies that passed too close to each other and merged together. See Figure 11.2

Figure 11.1 Cygnus A

It is estimated that the total power radiated by the galaxy is 10^{38} Watts – millions of times more than from the entire Milky Way. The radio emission is produced from a vast area that dwarfs the size of the galaxy – See Figure 11.3

Figure 11.2 Cygnus A (optical)

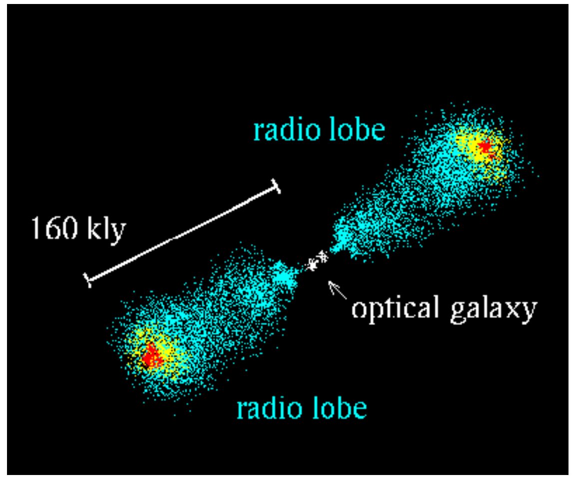


Figure 11.3 Cygnus A (Radio emission)

A professional radio image of Cygnus A can be seen in Figure 11.4 (Image courtesy of NRAO/AUI).

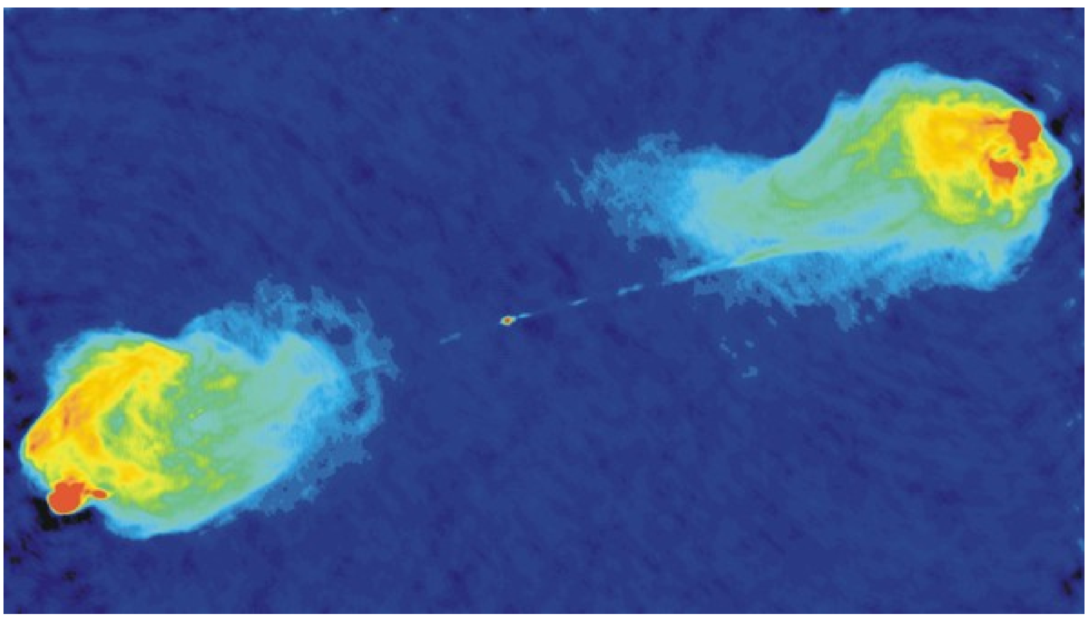


Figure 11.4 Radio image of Cygnus A showing the galaxy & radio lobes
(image produced at cm wavelength)

A problem arises for the amateur observer because Cygnus A is located close to Cygnus X (a powerful X ray source that also emits radio energy) and both lie within the galactic plane. It is therefore difficult to separate these components using small antennas with limited angular resolution. It is possible to observe at microwave frequencies where resolution is improved, but for frequencies below 2GHz the antenna beams are likely to encompass all the objects. See Figure 11.5 (Radio Eyes picture [11])

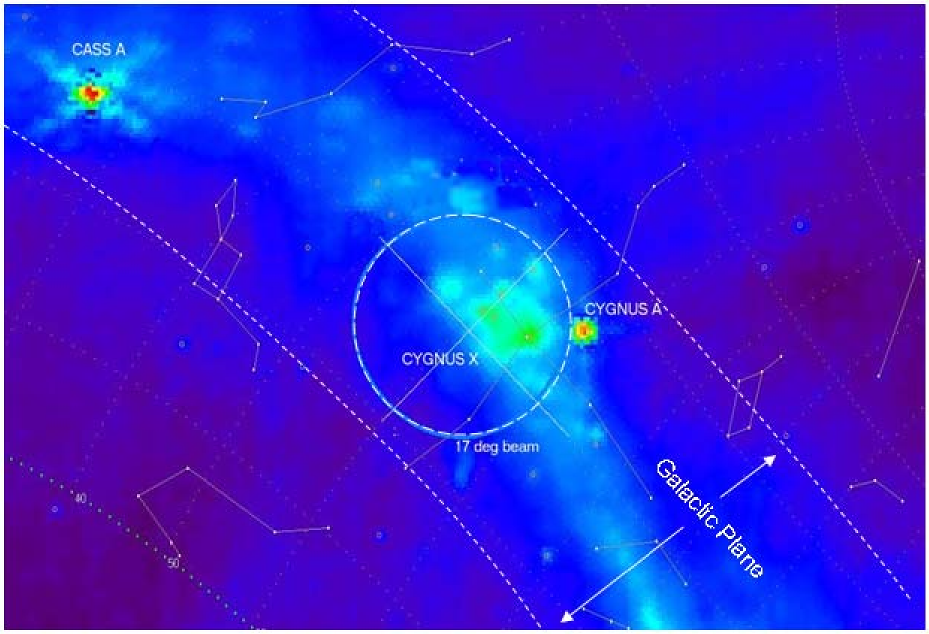


Figure 11.5 Cygnus sources embedded in the galactic plane

Probably the best way to pick out Cygnus A is to use an interferometer that will produce fringes for small diameter objects only (as discussed in section 8). A small sample of the fringe pattern recorded from Cygnus A with an amateur interferometer [21] is shown in Figure 11.6. Due to the strength of the source, the measurement goes 'off scale' but this serves to demonstrate that the detection and separation of Cygnus A from other objects is clearly possible for amateur observers to undertake.

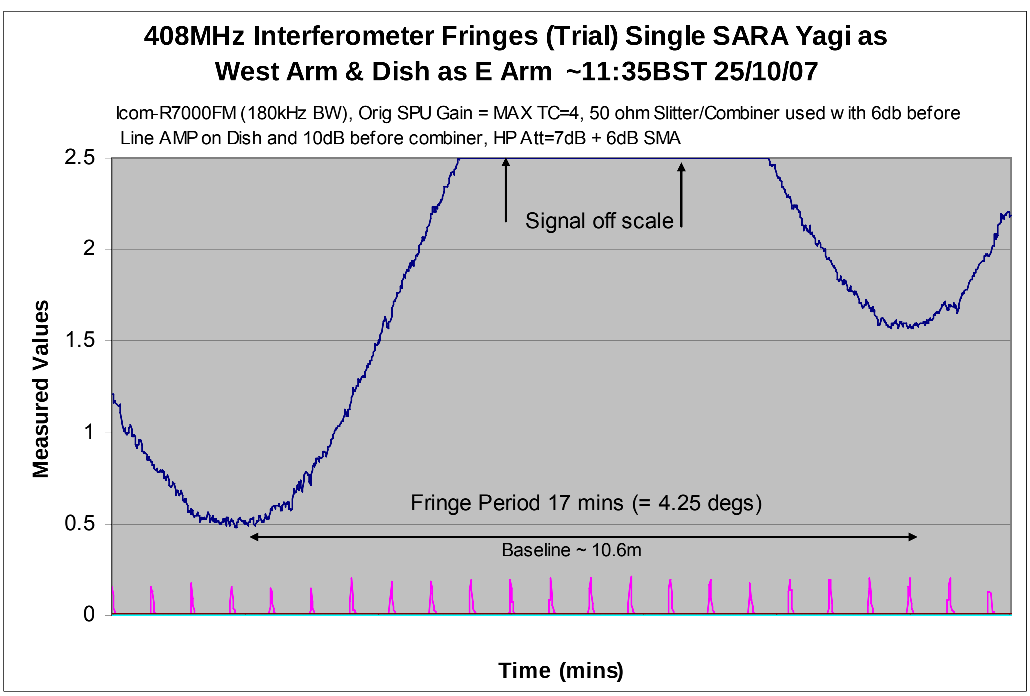


Figure 11.6 Part of fringe pattern from Cygnus A

11.3 Virgo A (M87)

This is a more challenging object to observe. The power flux density at 1420MHz is low, approximately 560Jy – See Figure 2.1.

Virgo A is a super-giant elliptical galaxy. It was discovered in 1781 by French astronomer Charles Messier and is the second brightest galaxy within the northern Virgo Cluster. See Figure 11.7. It is located about 53.5 million light years away from Earth.

Figure 11.7 Optical picture of the Virgo cluster of galaxies of which M87 is a member

M87 was identified with the radio source Virgo A by W. Baade and R. Minkowski in 1954. In 1956, a weaker radio halo was found by J.E. Baldwin and F.G. Smith of Cambridge. The galaxy has a spectacular jet which is better seen on short exposure photographs as shown in Figure 11.8 This is a directional beam of relativistic[+] plasma issuing from the core of the galaxy and contributes to its radio emissions.

Figure 11.8 Virgo A
(showing the relativistic jet)

The jet is thought to be produced by a violent active nucleus in the galaxy, probably a massive central object of several billion solar masses concentrated within the innermost sphere with a radius of 60 light years.

From Figure 11.9 it can be seen that it is fortunate that the Virgo A radio source lies well out of the galactic plane - toward the north galactic pole - as this enables it to be detected without clutter from the widely dispersed Galactic noise.

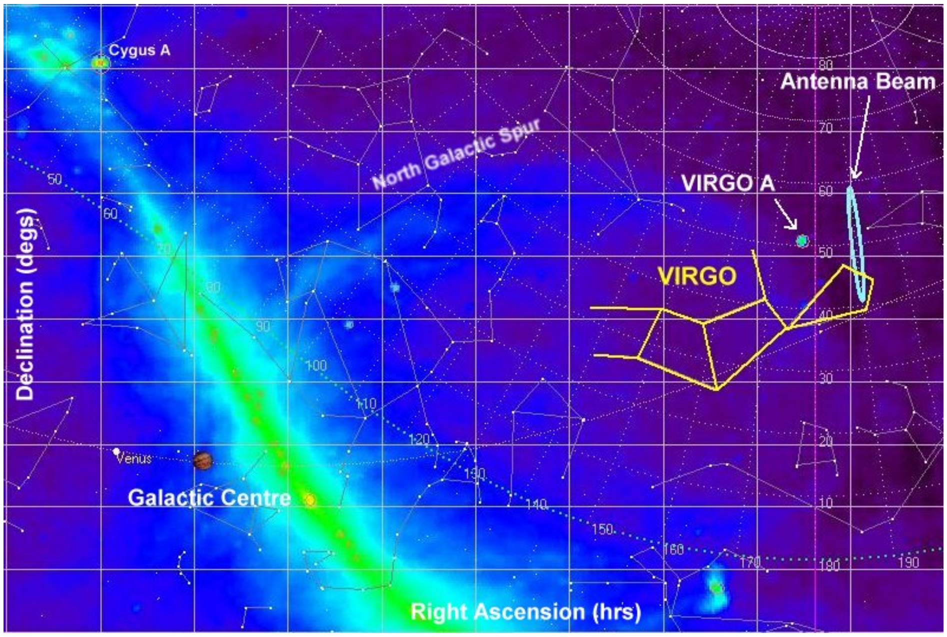


Figure 11.9 Location of Virgo A

+ Relativistic particles travel close to the speed of light

As the emission from Virgo A has a synchrotron-like spectrum - which can be seen in Figure 11.10 - to observe this source it is better to use as a low a wavelength as possible in order to receive the most signal.

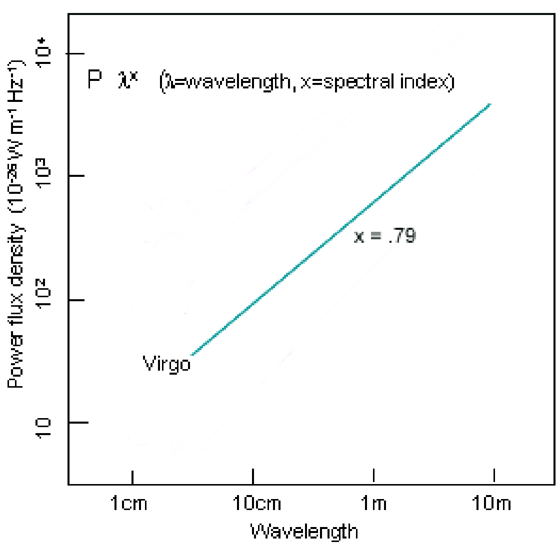


Figure 11.10
Emission spectrum of Virgo A

This usually means having the disadvantage of a wide antenna beamwidth that smears out the point source and the background. Again, by employing an interferometer a narrow beam can be ‘synthesised’ making the object easier to detect. In Figure 11.9 we see the central lobe of the interferometer antenna pattern with a width of 1.4^0 in the E-W (Right Ascension) direction.

The resulting fringe pattern is shown in Figure 11.11, confirming a good detection of this extra-galactic object.

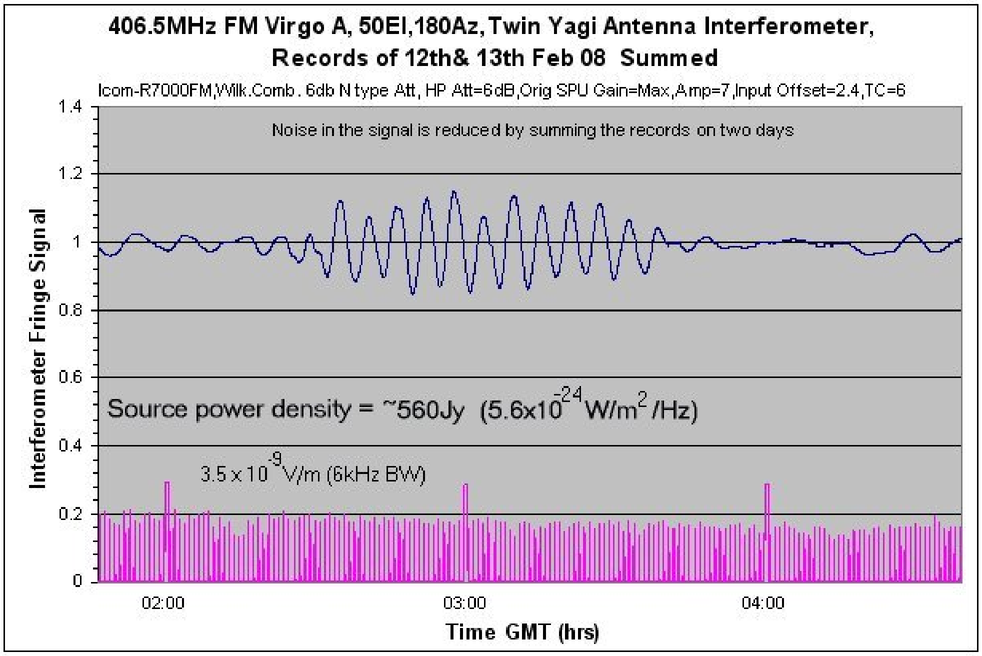


Figure 11.11 Amateur detection of Virgo A (406.5MHz interferometer)

12 Conclusions

Radio astronomy is a fascinating area of technical endeavour and, as this article shows, it is open to people with enquiring minds and some engineering skill. It does not require vast expenditure as much of the equipment can either be home-constructed or obtained from amateur radio outlets.

Some attention to detail is required and patience is needed to assemble and perfect the receiver system to enable the detection of very weak signals with stable gains and a constant low noise background.

Once equipment is in service one can begin by detecting the radiation from the Sun and some planets. Following this, observations can be made of the galactic emissions in the Milky Way. It is interesting to make maps of these emissions.

More exacting measurements can be made of supernova remnants within the galaxy. With amateur equipment it is not possible to map these sources, but detecting them is quite feasible.

Thermal emission nebulae also present a challenge, but again, one within reach of the amateur observer. The best choice is the Orion Nebula.

Pulsars are hard to detect. Only a few amateurs have succeeded using modest sized antennas of around 3m diameter. The configuration of the receiver chain is different from that used to detect steady signals from the sources discussed so far. The pulsed signals mean that integration over a period of time cannot be used as a technique to improve detectability. In the case of pulsars a lot of raw signal is needed – and this means large antennas. The use of purpose designed post detector software algorithms can improve detectability.

Finally, it is possible for an amateur radio astronomer to detect extra-galactic objects. Cygnus A is a very powerful radio source some 600 million light years away and is quite easy to detect. Virgo A, by contrast, is only 53 million light years away but is a much more difficult proposition.

It is hoped that this paper has indicated some of what an amateur observer can achieve and that interested persons will set up a radio telescope – however modest – and explore the fascinating range of radio objects in the sky.

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6 www.spaceacademy.net.au/spacelab/projects/jovrad/jovrad.htm
7 www.spacetoday.org/SolSys/Jupiter/JupiterRadio.html
8 http://www.radiosky.com/jupmodes.html
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10 http://scienceworld.wolfram.com/astronomy/GalacticCoordinates.html
11 Radio Eyes software www.radiosky.com
12 http://imagine.gsfc.nasa.gov/docs/science/know_l1/pulsars.html
13 http://www.naic.edu/~pulsar/gifs/wapp.gif
14 www.radioastronomy101.com/radio_astronomy_sections/attachments/1-13-Radio-Astronomy-Source-Verification.pdf
15 www.radio-astronomy.org/pdf/pulsars.pdf
16 www.radio-astronomy.org/
17 www.radio-astronomy.org/pdf/pulsars.pdf
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