Chapter 4

Beyond the Solar System

Before we discuss specific details about radio objects outside our Solar System it is appropriate to introduce some fundamental concepts of radio astronomy and the basic scientific measurements gathered by radio telescopes. In this section we will introduce the units of measurement used to compare the relative strengths of radio objects in the sky.

Brightness and Flux Density

It is very important to understand the concepts of brightness and flux density. The ideas are simple enough but easily confused with each other. These concepts are not unique to the radio spectrum, of course. They apply for all electromagnetic radiation (Fig. 4.1).

Let's consider the simplest case where radiation travels through empty space. It is not absorbed or scattered along the way, and there are no extra emission sources on route.

The ray-optics approximation considers the energy to be flowing in straight lines. This approximation is valid only if the source is physically much larger than the wavelength of the radiation. Clearly this is true for astronomical sources such as planets, stars, and nebulae.

Now consider the Sun, which appears to have a nearly uniform "brightness" distribution across its face. If a camera is used to take its picture, the exposure used would not vary whether it was taken from Venus, Earth, or Mars. Only the angular diameter of the Sun would vary. The Venus photograph would not be overexposed, and the Mars photograph would not be underexposed. The number of photons falling on the film per unit area per unit time per unit solid angle remains constant, regardless of distance. In other words the intrinsic brightness of the Sun does not change with distance.

The number of photons falling on the film per unit area per unit time does decrease with distance. Therefore brightness or specific intensity is a measure of the energy received per unit area per unit time per unit solid angle. While the flux is the energy received per unit area per unit time, specific intensity is constant. Flux reduces

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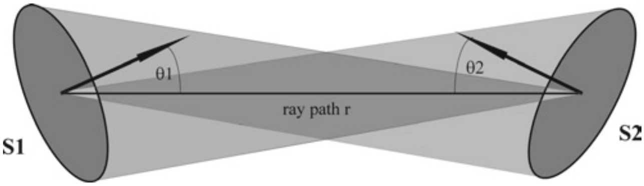

Fig. 4.1. Specific intensity. Our normal thoughts of brightness relate to the intensity of a source per unit area. This clearly decreases with distance from the source. However, specific intensity is the power per unit area per unit solid angle Θ per hertz. This is constant at any distance from the source.

in inverse proportion to the square of the distance from the source. Other names for "brightness" are spectral intensity, spectral brightness, and spectral radiance.

Specific intensity is therefore conserved (constant) along any ray in empty space (no absorption or scattering) in which case the brightness can be considered as energy flowing out of the source, or as energy flowing into our detector.

For discrete sources (those that subtend a well-defined solid angle) the spectral power received by the antenna of unit area is called the flux density. If a source is unresolved by the telescope, then its flux density can be measured, but its specific intensity cannot. If a source is much larger than the point source response and is resolved, the spectral intensity can be measured directly, but the flux density must be calculated by integrating the spectral intensity over the source's solid angle.

The unit of flux density is $Wm^{-2}\ Hz^{-1}$. A value of 1 $Wm^{-2}\ Hz^{-1}$ is a large figure in radio astronomy, so the Jansky was introduced, where 1 Jansky = $10^{-26}\ Wm^{-2}\ Hz^{-1}$.

For most objects observed with small radio telescopes, including the Sun, we can only determine the flux density.

Often in radio astronomy the brightness, or specific intensity, of an object is given as a temperature. Quantum mechanics provides a relationship between received power and wavelength that is accurate over the whole of the electromagnetic spectrum in the Planck equation. However it is cumbersome to work with, whereas for the restricted bandwidths of the radio spectrum the Rayleigh–Jeans law is a good approximation. The Rayleigh–Jeans formula relates power to temperature and wavelength:

$$P = \frac{2\pi kT}{\lambda^2} Wm^{-2} Hz^{-1}$$

where P is the power emitted by 1 m^2 of a blackbody surface whose temperature is T kelvin, over a bandwidth of 1 Hz at the wavelength of λ. K is the Boltzmann constant

We know, however, that the flux density is attenuated by the inverse square law as the radiation travels outward from the source. The amount of attenuation is:

$$attenuation\ due\ to\ distance = \left(\frac{R}{d}\right)^2$$

where R is the radius of the source and d its distance from us.

We can then modify the Rayleigh–Jeans equation to relate our received flux density to the temperature and wavelength like this:

$$S = \frac{2\pi kT}{\lambda^2}\left(\frac{R}{d}\right)^2 Wm^{-2} Hz^{-1}$$

where S is our measured flux density.

Continuum Emission

Fundamentally, radio emission falls into two broad classes, thermal and non-thermal. Thermal emission occurs from a system whose population state is associated with the Maxwell–Boltzmann velocity distribution, which is dependent on the kinetic temperature T. The intensity of the emission may depend on various parameters, but it will certainly be a function of the temperature. In a heated gas or plasma the motion of the particles is random, and emitted radiation therefore exhibits no specific polarization. In practice temperatures greater than 10^8 K are rarely encountered, so if a derived temperature is higher than 10^8 K the chances are it is of non-thermal origin. Non-thermal radiation is everything else and is caused by charged particles being accelerated (or decelerated) in the presence of an electric or magnetic fields, or when particles collide with other particles whose velocity distribution does not match the Maxwellian profile.

Thermal Bremsstrahlung Spectrum

Bremsstrahlung is a word derived from the German language for "braking radiation." It occurs when a free electron travels close to but does not combine with a positively charged atomic nucleus or ion. Another name given to Bremsstrahlung radiation is free-free emission, referring to the fact that the electron is free before and after the emission of a photon (Fig. 4.2).

The emission occurs when the electron encounters an electrostatic force, deflecting it in its in path and therefore emitting a radio photon. Because energy must be conserved the result is to slow down the electron, hence the name "braking radiation." In nature the deflection angle is usually small, and the associated change in velocity negligible, resulting in very low energy photon emission in the radio spectrum.

The spectrum of Bremsstrahlung radiation will have a sharp cutoff at upper and lower ends. At the low frequency end the emission is from electrons that approach the nuclei closely, and the cutoff occurs because closer encounters involve election capture. The high-frequency emission is limited by the temperature of the gas, so if this cutoff can be observed it is all the information required to provide a measure of the gas temperature. Note here the upper cutoff may be outside of the radio spectral window depending on cloud temperature.

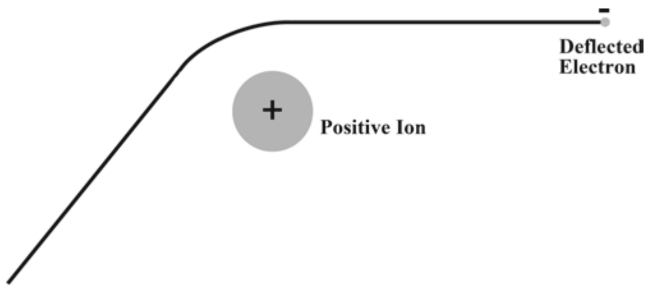

Fig. 4.2. A fast-moving electron passing close to a slow-moving heavy ion is deflected and loses a small amount of energy in the form of a radio photon.

Bremsstrahlung is often the dominant process for radio emission from ionized HII clouds and planetary nebulae. Study of the Bremsstrahlung spectrum can yield information on the density of the cloud. Radio studies are by far the best way to obtain this information. Radio waves are not scattered or attenuated by the interstellar medium (ISM) because the wavelength is much greater than the average particle size of the ISM. Scattering or attenuation of light often requires uncertain corrections to be applied to observations. Once a measure of the density is known the mass of the cloud can be determined from its volume. The assumption for cloud volume is, it is about as deep as it is wide.

Cyclotron and Synchrotron Radiation

In a similar way to Bremsstrahlung, emission of energy occurs from electrons deflected in a magnetic field. In the synchrotron case, the electrons have relativistic velocities (close to the speed of light), and for cyclotron emission the electron velocity is much less than that of light. Occasionally this process is referred to as magneto-Bremsstrahlung.

The electron traveling in a magnetic field experiences a Lorentz force, which is perpendicular to both the velocity and magnetic field vectors. The velocity vector can be at any angle to the magnetic field and is known as the pitch angle (Fig. 4.3).

The result of an arbitrary pitch angle is that the electron will move parallel to the magnetic field in a spiral path. If the field line curves, then the spiral path curves with it. The electron is trapped in the field. In the special case of a zero pitch angle the electron will move in a circular path around the magnetic field. The other special case of a 90° pitch angle means the electron is unaffected by the field.

Consider first the cyclotron case. Cyclotron radiation is emitted at the gyrofrequency. When viewed from a direction along the field line, the electric vector of the emitted radiation will be seen to rotate, therefore giving rise to circularly polarized emission. When viewed from the side, however, the motion of the electron appears to oscillate from side to side, and therefore the polarization will be linear. For all viewing angles in between the emission will appear to have elliptical polarization. For this reason polarized radio emission is a definite indication of a magnetic field within the source.

Note that the gyrofrequency is independent of the electron velocity. The radius of the circular or spiral motion (the gyroradius) is defined only by the strength of the magnetic field, so the gyrofrequency is also only dependent on the magnetic field strength. The gyrofrequency has a very simple relation to the field strength given by the following formula:

$$f = 2.8B$$

where f is the gyrofrequency in hertz and B is the magnetic field strength in gauss.

Clearly, if the cyclotron frequency can be measured, the strength of the field can be immediately determined. However, plasmas exhibit a critical frequency known

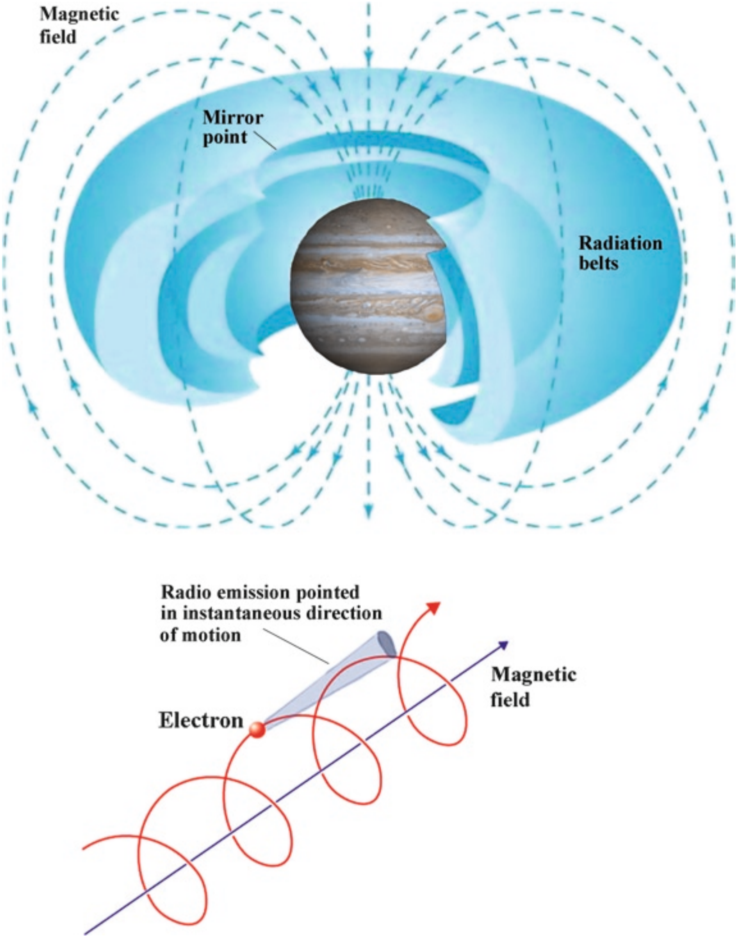

Fig. 4.3. The cyclotron/synchrotron emission process from trapped electrons in a magnetic field.

as the plasma frequency, such that a wave emitted within it must have a frequency higher than the plasma frequency in order to escape, or else it will be reflected. On top of this remember that Earth's ionosphere is also a plasma, and therefore the cyclotron emission has to have a frequency higher than the ionospheric plasma frequency to be observable by ground-based stations.

As an example the warm ionized medium (WIM) of the interstellar regions of our Milky Way Galaxy will emit cyclotron radiation. If the magnetic field strength here is 3 μG and the temperature is 10^4 K the frequency of emission will be 8.4 Hz. Not only will this not penetrate our ionosphere, it will not even escape the WIM because its plasma frequency will be 890 Hz. As we saw in the chapter on Jupiter, though, the strong field of the Jovian environment does allow us to study a good proportion of the Jovian cyclotron emission. The field strength of any object must be greater than 3.5 G or higher in order for cyclotron emission to penetrate our ionosphere, assuming a cutoff of 10 MHz.

Where the magnetic field of the ionized region varies smoothly (such is the case for Jupiter) the cyclotron emission will give a continuum spectrum with a sharp cutoff occurring at the point of maximum field strength.

The Synchrotron Spectrum

Synchrotron emission occurs from electrons traveling at relativistic speeds within a magnetic field. This is a common process occurring throughout the universe. Now, the mass of the electron is increased by a factor γ known as the Lorentz factor. This increases the gyroradius and decreases the gyrofrequency compared to the cyclotron case.

The transformations required between the rest frame of the electron (the frame of reference moving with the electron) and the rest frame of the observer result in the total power being boosted by a factor γ^2. The power as seen by the observer is distributed over a conical pattern whose angle is $1/\gamma^2$. This cone is directed in the path of the instantaneous velocity vector, and only if the cone passes through the observer's line of sight will it be detectable. For high-energy particles the cone of emission is small compared with the gyration frequency, so the energy is pulsed as the cone briefly sweeps past the observer's line of sight. The duration of the pulse defines the highest observable frequency. However, most emissions occur at lower frequencies, which are harmonics of the fundamental gyrofrequency; the result of the significant reduction of the gyrofrequency is that these harmonics are very close together. This means synchrotron emission is essentially continuous and spread over a broad spectral range. Due to the emission occurring significantly above the fundamental gyrofrequency even small magnetic fields produce observable emission, making synchrotron radiation more commonly observed than cyclotron.

Synchrotron radiation is unrelated to temperature. The electron velocities do not follow a Maxwellian distribution. Hence the observed "temperature" can appear excessive, and it is therefore classed as a non-thermal emission.

When analyzing the spectrum of synchrotron sources the results can be a jumble of other emission such as thermal Bremsstrahlung, as would be the case for a supernova remnant. Also in objects such as active galactic nuclei optically thick emission is common, but the spectral detail is complex due to the emission from heavier particles being superimposed on the electron synchrotron spectrum. However if the synchrotron component can be clearly observed, it can be used to measure the magnetic field strength. The rise of the spectrum to the peak value comes from optically thick emission. Optically thick refers to the probability of particle collision resulting in recombination. The depth of the cloud is much greater than the mean free path of the particles, and we cannot see all the way through the cloud. The brightness of the source is therefore independent of the density. From a single measurement of the optically thick spectrum it is possible to determine the strength of the field perpendicular to the observer's line of sight. From a statistical combination of observations an average of the readings will give an approximate value of the overall field strength.

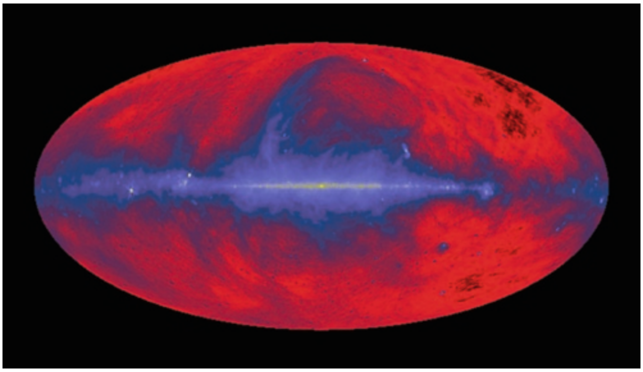

Fig. 4.4. The radio sky at 408 MHz. (C. Haslam et al. Max Planck Institute for Radio Astronomy.) The emission is largely due to synchrotron radiation for our galaxy.

The portion of the synchrotron spectrum beyond the peak, as it falls to minimum, is generated is a power law slope and is characteristic of optically thin emission (where the mean free path is greater than the depth of the cloud, the cloud is transparent). The power law slope is a consequence of the electron energy distribution and means the spectrum is a function of both the particle density and the magnetic field. Unfortunately it is not possible to determine the particle density alone without first knowing the magnetic field strength B. As indicated previously, it is not always possible to isolate the optically thick spectral component to determine B. In such cases, by making some estimates and assumptions it is still possible to extract information on the magnetic field strength and particle energies from observations of the optically thin spectrum, which unlike the optically thick is readily observable.

For the same reason as cyclotron, synchrotron emission is intrinsically polarized. Thermal Bremsstrahlung is never polarized, so the presence of polarization is a good indication that the synchrotron mechanism is the cause (cyclotron emission is rarer and restricted to long wavelengths). However, as always, the reality is not always so clear; in sources of large extent such as the interstellar medium of our Milky Way, the magnetic field can be twisted and more randomly distributed. The consequence is that the combined response across the source region averages out and polarization is mixed. For cases where polarization clearly exists, then synchrotron emission is certain, but the absence of polarization does not rule it out.

The image presented in Fig. 4.4 shows a map of the sky at 408 MHz, consisting of mostly synchrotron emission.

The various sources of radiation in the image include supernovae remnants, shock waves in the interstellar medium, stellar jets, some binary stars, and pulsars; even cosmic rays passing through the interstellar medium can produce interactions generating radiation. The magnetic field pervading the Milky Way may amount to only a few micro gauss, but this is sufficient to produce observable radio radiation.

Extragalactic sources of synchrotron energy include active galactic nuclei powered by super massive black holes, which generate enormous bipolar jets of particles. Two of the brightest examples are Centaurus A and Cygnus A.

Inverse Compton Scattering

Inverse Compton scattering does not tend to produce output in the radio spectrum, but it does potentially reduce the amount of radio photons emitted.

Compton scattering is where a high-energy photon in the X-ray to gamma ray spectrum collides with an electron imparting energy to the electron, and the result increases the wavelength of the initial photon. The inverse process also occurs, where a high-energy electron impacts a low-energy photon, thus decreasing the photon wavelength and pushing it into the visible or higher spectral range. The sources producing Inverse Compton (IC) radiation also produce synchrotron emission, but not all synchrotron sources produce IC.

For sources of a given number of relativistic electrons, if the radiation field is weak and the magnetic field is strong, synchrotron output will dominate. For the inverse case of a weak magnetic field and a strong radiation field, IC radiation will be the dominant process.

Emission Line Radiation

Emission lines exist throughout the electromagnetic spectrum and occur when bound electrons change their quantum energy state from a high level to a lower level, emitting a photon in the process. Because in general the electrons can only hold discrete energy states, then where a large population undergo the same transitions continuously an emission line can be observed. In this section only the radio frequency emission lines will be considered.

Hydrogen is the most common element in the universe, so the significance of rare transitions of electron quantum state can be measured in practice. The highest quantum states for the electron in a hydrogen atom, where $n > 40$, have energy levels that are very close together. Transitions at these high-energy levels will emit radiation in the radio spectrum. In comparison to the emission at lower levels of the atom, which give optical output, these high transitions are rare. It is believed possible that quantum numbers up to 1,600 are possible, where the electron would be placed 0.3 mm from the nucleus!

Line emissions from hydrogen, known as the Radio Recombination Lines (RRL's), can make it possible to study HII regions that would otherwise be obscured by the intervening interstellar medium, which generates so much extinction to optical telescopes. When observing RRLs several assumptions can be made:

- RRLs are weak and can be observed at the optically thin limit.
- The downward transition is a strong function of quantum number, and the time scale for de-excitation becomes very long with high quantum numbers.
- At radio wavelengths the Rayleigh–Jeans approximation to the Planck function can be used.

The optically thin emission of the source holds information about the temperature and density of the gas cloud, but the observation of a single RRL is unable to provide enough information to be able to determine one property without knowing the other first. However, the same ionized gas will emit thermal Bremsstrahlung continuum emission. The ratio of line intensity to continuum emission in the vicinity of the line can yield a value for the electron temperature.

The HI 21 cm Emission Line of Hydrogen

The quantum energy change involved in the emission of 21 cm radiation is known as the hyperfine transition of the electron ground state, where the electron spontaneously reverses its spin property. The electron ground state is where the electron is at its closest to the proton nucleus. Therefore it originates from the cold hydrogen that pervades the interstellar medium. This cold hydrogen exists as single hydrogen atoms, unlike the molecular H_2 involved in the ionized clouds surrounding young stars.

The classical model of the hydrogen atom is that of an electron orbiting a proton; the electron is spinning either clockwise or anticlockwise. In the quantum age we now know this model is not accurate, but it is still a useful way of picturing the process in the mind's eye. The hydrogen atom has slightly higher energy if the spin of the electron and proton are the same (parallel spin), and slightly lower energy when the spins are anti-parallel. As with many of the hyperfine transitions emanating from a split quantum state, it is known as a forbidden line. As such the time interval between transitions is extremely long, in the order of 10 million years or more in this case. However, hydrogen is so common in the universe that the radiation is easily observed by radio telescopes.

The rest frequency of emission is 1420.40575177 MHz in the L band. However the Doppler shift in frequency is easily observed, which can quickly give a measurement to the rotation speed of our Milky Way. Theoretically, at least, the study of red-shifted 21 cm emission in the range of 200 MHz down to the ionospheric cutoff about 10 MHz can be used to probe the state of the early universe. In practice this is extremely difficult from Earth's surface due to interference from manmade sources and in isolating the weak signals from the background continuum previously discussed.

Following is a table of the most important molecular emission lines in the radio spectrum up to a maximum of 100 GHz.

Molecule	Rest frequency
Deuterium (DI)	327.348 MHz
Hydrogen (HI)	1,420.406 MHz
Hydroxyl radical (OH)	1,612.231 MHz
Hydroxyl radical (OH)	1,665.402 MHz
Hydroxyl radical (OH)	1,667.359 MHz
Hydroxyl radical (OH)	1,720.530 MHz
Methyladyne (CH)	3,263.794 MHz
Methyladyne (CH)	3,335.481 MHz
Methyladyne (CH)	3,349.193 MHz
Formaldehyde (H_2CO)	4,829.660 MHz
Methanol (CH_3OH)	6,668.518 MHz
Helium ($^{3}He^{+}$)	8,665.650 MHz

(continued)

Molecule	Rest frequency
Methanol (CH_3OH)	12.178 GHz
Formaldehyde (H_2CO)	14.488 GHz
Cyclopropenylidene (C_3H_2)	18.343 GHz
Cyclopropenylidene (C_3H_2)	21.587 GHz
Water vapour (H_2O)	22.235 GHz
Dicarbon monosulphide (CCS)	22.344 GHz
Ammonia (NH_3)	23.694 GHz
Ammonia (NH_3)	23.723 GHz
Ammonia (NH_3)	23.870 GHz
Ammonia (NH_3)	24.139 GHz
Methanol (CH_3OH)	36.169 GHz
Cyanoacetylene (HC_3N)	36.392 GHz
Silicon monoxide (SiO)	42.519 GHz
Silicon monoxide (SiO)	42.821 GHz
Silicon monoxide (SiO)	42.880 GHz
Silicon monoxide (SiO)	43.122 GHz
Silicon monoxide (SiO)	43.424 GHz
Dicarbon monosulphide (CCS)	45.379 GHz
Cyanoacetylene (HC_3N)	45.490 GHz
Carbon monosulphide (^{13}CS)	46.247 GHz
Carbon monosulphide ($C^{34}S$)	48.207 GHz
Carbon monosulphide (CS)	48.991 GHz
Oxygen (O_2)	56.265 GHz
Oxygen (O_2)	58.324 GHz
Oxygen (O_2)	58.446 GHz
Oxygen (O_2)	59.164 GHz
Oxygen (O_2)	59.591 GHz
Oxygen (O_2)	60.306 GHz
Oxygen (O_2)	60.434 GHz
Oxygen (O_2)	61.151 GHz
Oxygen (O_2)	62.486 GHz
Deuterated formylium (DCO^+)	72.039 GHz
Deuterium cyanide (DCN)	72.415 GHz
Cyanoacetylene (HC_3N)	72.784 GHz
Methyl cyanide (CH_3CN)	73.59 GHz
Deuterated water (HDO)	80.578 GHz
Cyanoacetylene (HC_3N)	81.881 GHz
Cyclopropenylidene (C_3H_2)	82.966 GHz
Cyclopropenylidene (C_3H_2)	85.339 GHz
Methyl acetylene (CH_3CCH)	85.5 GHz
Deuterated ammonia (NH_2D)	85.926 GHz
Hydrogen cyanide ($HC^{15}N$)	86.055 GHz
Silicon monoxide (SiO)	86.243 GHz
Hydrogen cyanide ($H^{13}CN$)	86.340 GHz
Formylium ($H^{13}CO^+$)	86.754 GHz
Hydrogen isocyanide ($HN^{13}C$)	87.091 GHz
Silicon monoxide (SiO)	86.847 GHz
Ethynyl radical (C_2H)	87.300 GHz
Hydrogen cyanide (HCN)	88.632 GHz
Hydrogen isocyanide($H^{15}NC$)	88.866 GHz
Formylium (HCO^+)	89.189 GHz
Hydrogen isocyanide (HNC)	90.664 GHz
Cyanoacetylene (HC_3N)	90.979 GHz
Methyl cyanide (CH_3CN)	91.98 GHz

(continued)

Molecule	Rest frequency
Carbon monosulphide (^{13}CS)	92.494 GHz
Diazenylium (N_2H^+)	93.174 GHz
Carbon monosulphide (C^{34}S)	96.413 GHz
Carbon monosulphide (CS)	97.981 GHz
Sulphur monoxide (SO)	99.300 GHz

The 3 K Microwave Background

Our Milky Way Galaxy is pretty noisy in the HF and VHF. The sky background brightness when expressed as a temperature is hundreds of kelvin at a wavelength of 1 m, but at a wavelength of 0.1 m the cold sky background is only 3 K. This signature is the background radiation left over from the Big Bang, which formed the universe. This temperature, therefore, establishes a limit to the sensitivity that is possible for a radio telescope. In fact in most cases the noise performance of a radio telescope will be limited by the thermal noise produced within the first amplifier stage for a telescope operating at centimeter wavelengths or less. Professional instruments are cooled with liquid nitrogen to improve their performance.

Radio telescopes working at meter wavelengths can cope with much higher noise levels generated within the electronics, but ideally the first amplifier stage (which contributes most to the overall noise performance) should be better than the background sky level. In practice this should not be difficult to achieve.

Pulsars

Most of this chapter so far has covered general topics on the observation of the Milky Way and extragalactic objects, the bread and butter radio sources being ionized gas clouds or neutral cold gas clouds. One type of object warrants special attention – the pulsars.

The first pulsar was discovered in 1967 by Jocelyn Bell and Anthony Hewish using a phased array of 2,048 dipole antennae spread over a 4-acre field. They were working at a frequency of 81.5 MHz. Pulsars are cataloged with a prefix of PSR, followed by their location in right ascension and declination. For example the first pulsar discovered by Jocelyn Bell at Cambridge is PSR 1919+21. This decodes to a right ascension of 19h19m and a declination of +21°.

Pulsars show the following properties:

- Most have periods between pulses of between 0.25 and 2 s, although some millisecond pulsars are known, and the longest is over 8 s.
- The pulse period is extremely stable and repetitive.
- Pulsars spin down over time but very slowly. Their characteristic lifetimes (the time it takes for pulses to stop if the spin down rate remains constant) varies but are expected to be hundreds of millions of years.

Pulsars were discovered accidentally during an experiment to investigate scintillation of radio waves. The almost artificial regularity of the pulse train suggested alien intelligence, although this was quite quickly ruled out. The very rapid pulses could only be explained by a very compact spinning object. This ruled out the possibility of their origin from binary star motion, pulsating variable stars, or even conventional stellar rotation rates. Thomas Gold postulated the emission was generated from a rapidly rotating neutron star.

Indeed, within a year of discovery, pulsars were detected within the Vela and Crab nebulae supernovae remnants. Once an average-mass star runs out of fuel, the core collapses, and the outer gaseous envelope is blown off in either a planetary nebula or by a supernova, depending upon the initial mass. The collapsed core of objects less than 1.4 solar masses form white dwarves – consisting of a degenerate compact soup of free protons, neutrons, and electrons. However, if the mass is between 1.4 and 3 times solar masses, the gravitational contraction is sufficient to increase the density so much as to force the nucleons very close together. This converts all protons into neutrons. The result is a degenerate soup of neutrons, quarks, etc., and is known as a neutron star. The neutron "fluid" is expected to be superconducting at temperatures up to 10^9 K. More massive stars after a supernova explosion would form black holes. A neutron star of 1.4 solar masses with a period of 1.4 ms could be as small as 40 km across, though the average object would be somewhat larger. They are all considerably smaller than Earth.

How do we know this? After all, neutron stars have not been observed directly.

Consider the rotational period of the neutron star. The pulse period gives a direct measurement of the rotational period of the star. From simple physics, the minimum radius would be such that the centrifugal forces would balance the gravitational contraction, or else it would break up. The figures calculated for a 1.4 solar masses object reveal radii as small as 20 km. Now that the minimum dimension is known the minimum density can be estimated. From this, the period of the first pulsar to be discovered (1.3 s) would suggest a density consistent with white dwarf stars. However, once faster objects such as the Crab Nebula ($p = 0.033$ s) were found, the implied density of $>10^{14}$ g cm^{-3} could not be explained as a white dwarf and so must be a neutron star. From the observations of several pulsars whose mass could be determined (from their mutual revolution around other massive objects nearby) they all appeared to be very close to 1.4 solar masses. These high spin rates are accounted for by the conservation of angular momentum as the core collapses.

The mechanism of radio generation is poorly understood but will involve synchrotron processes. You will be familiar with Earth and its magnetic field. The rotational axis of Earth does not match that of the magnetic field. We have already seen for Jupiter, the planetary dipole field is tilted about 10° with respect to Jupiter's rotational axis; this situation is common and is true of neutron stars and therefore pulsars, too. Energy is beamed from the magnetic poles, in a north and south direction. As the neutron star rotates, the radio beam sweeps quickly past our line of sight, and we see it as a pulse of radiation. If we assume that all neutron stars beam radiation from their poles, clearly then we cannot observe all neutron stars by means of pulsed radio output, but statistically a few will have a suitable orientation for us to study them.

Pulsed output from neutron stars is not restricted to radio energy but can be seen throughout the electromagnetic spectrum, at least in some cases. The Crab pulsar can even be seen flashing in the optical spectrum, although very high time resolution is required, or the use of a rotating shutter to effectively slow down the pulses. The white light glow of the surrounding nebula shows significant polarization and is also associated with synchrotron emission, which is consistent with a magnetic field within the cloud of around 10^{-3} G.

This was puzzling at first, because the expansion of the nebula should have considerably weakened the field by now. The amount of power needed to maintain the expansion, the relativistic electrons, and the magnetic field is many times the output of our own Sun. All this power is coming from the pulsar. The pulsed radiation from the poles could not be the primary mechanism powering the nebula because it is 200 million times too small. It turns out the amount of power required to explain the properties of the nebula balance with the amount of power lost from the neutron star due to its spin down rate.

One idea for the energy loss mechanism is that the rotation of its magnetic field (polarization of the radio waves shows there is a field) induces a complementary electric field at a distance from the star. This forms an electromagnetic wave called magnetic dipole radiation. The magnetic field of a neutron star is expected to be very great, due to the conservation of magnetic flux, as the core initially collapses. This can magnify the strength of the field by as much as 10^{10} times. It is possible that a dynamo-like effect may increase this even more. The magnetic dipole radiation generated from the strong field would be of very low frequency, <1 kHz. Not only would that not penetrate Earth's atmosphere, it would not even escape through the interstellar medium. However, it is thought that magnetic dipole radiation is the primary energy loss mechanism driving the slow spin down rates of pulsars.

Certainly there is a substantial magnetosphere around the pulsar. Huge electric forces pull electrons and charged particles from the star. The magnetosphere corotates with the magnetic field, and the angular velocity will therefore increase with distance from the neutron star. However, the velocity can never exceed the velocity of light, so particles in the outer magnetosphere are spun away in a sort of wind, carrying the magnetic field with them into the surrounding cloud.

The Crab pulsar is relatively young; in fact, the supernovae was noted in historical records in 1054. These young pulsars show random glitches in the rotation period, where the periods decrease by between 10^{-6} and 10^{-8} s, with intervals of several years. The pulses are sharp and short, accounting for only 1–5% of the pulse period in time. However interaction with electrons in the interstellar medium slows down the radio waves, rather like light slows down when passing through a higher density refractive medium. The slowing process is wavelength dependent. Longer wavelengths slow down most. This turns a sharp "tick" of a pulse into a drawn-out descending pitch whistle. The amount of dispersion can be used to estimate the pulsar's distance. Pulse shapes vary widely, in that individual pulses can be a group of close sub-pulses. The sub-pulse structure may also vary with time, although by averaging these pulses over 100 or more cycles, the overall shape remains stable.

Pulsars are exceedingly difficult to detect. Their initial discovery was a very lucky accident, noted by a very keen-eyed astronomer. Jocelyn described the first recordings as "a bit of scruff," a short burst of energy recorded on a pen chart where she noted its regularity, and its return 23 h and 56 min later guaranteed its celestial origin. In the major radio surveys conducted by the large radio telescopes the typical limiting sensitivity was about one Jansky. By a sheer coincidence, the mean flux density at meter wavelengths of the strongest pulsars is about one Jansky. Let's say the background electrical noise in the 250 foot mark 1 Jodrell Bank telescope was 100 Jansky, which itself is operating with a noise temperature of 100 K. Pulsars therefore have a signal 10^{-4} times that of the noise, and even then the pulses are only near their peak output up to 5% of the time. If the bandwidth was 1 MHz and the integration time of the receiver was, say, 10 ms, which is reasonable, then the sensitivity would be 100 times better than the noise, but in order to observe a single pulse it would still have to be considerably stronger than one Jansky and lasting more than 10 ms. Clearly special techniques were required.

Increasing the integration time did not help. In order to observe detail in the pulses more than two samples would be required in a pulse period, ideally considerably more. One technique that was used was to integrate the signal by superposing pulses together over a period of time. It helps to already know the period, of course, but with heavy post processing and trial and error the period of an unknown pulsar could be obtained.

Although observing pulsars at meter wavelengths is exceedingly difficult, the problem eases somewhat in the microwave region. Pulsars can be observed by radio methods at frequencies of between 20 MHz and 10 GHz. At least in the microwave region the sky is very cold and noise free. The telescope is then limited only by the local electrical noise and the noise temperature of the telescope front end. Low noise amplifiers and cooling with liquid nitrogen makes the job of pulsar studies easier.