1

Introduction

1.1 The role of radio observations in astronomy

The data give for the coordinates of the region from which the disturbance comes, a right ascension of 18 hours and declination of -10°.

(*Karl G. Jansky 1933*)

Jansky's discovery of radio emission from the Milky Way is now seen as the birth of the new science of radio astronomy. Most astronomers remained unaware of this momentous event for at least the next decade, and its full significance became apparent only with the major discoveries in the 1950s and 1960s of the 21-cm hydrogen line, the quasars, the pulsars and the cosmic microwave background. These are now fully assimilated into astronomy, and radio is now regarded as one among the several tools available to astronomers in their pursuit of the astrophysics of our Galaxy, or of neutron stars, black holes or cosmology. Nevertheless, radio astronomy has its own distinctive character, not least in its techniques and the particular expertise which they demand. It also has several fields of application in which it is uniquely useful: there is no other way of exploring the cosmic microwave background, it allows spectroscopic investigation of molecular clouds in the Milky Way and it reveals a previously unseen Universe through the synchrotron emission of high-energy particles in stars, galaxies and quasars.

The history of this development is outlined at the end of this book in Appendix 3. Our purpose in the main text is to set out those parts of astrophysics and observational techniques which are particularly appropriate in radio astronomy, so that the subject may be fully available to all astronomers and to physicists with a wide range of backgrounds. There is, throughout all radio astronomy, a close relation with other wavebands, and we shall acknowledge, for example, the necessity of using optically measured redshifts for distances of quasars and the components of gravitational lenses, and the need to bring together the X-ray and radio observations to obtain a coherent picture of neutron stars in our Galaxy.

The Milky Way, our Galaxy, which is the origin of the radio noise first observed by Jansky, is a complex assembly of stars of widely varying ages, embedded in an *interstellar* *medium* (ISM) of ionized and neutral gas, itself displaying a great diversity and complexity throughout the electromagnetic spectrum. Optical astronomy primarily addresses the surfaces of the stars, or nearby gas ionized by those stars, where the temperatures bring thermal radiation naturally into the visible range. X-ray astronomy deals with much hotter regions, such as the million-degree ionized gas which is found in such diverse places as the solar corona and the centres of clusters of galaxies. Infrared astronomy studies relatively cool regions, where thermal radiation from the dust component of the ISM is a prominent feature; warmer regions are also studied, where the thermal radiation from star-forming regions is also strong. Radio astronomy, using much longer wavelengths, addresses a broad range of both thermal and non-thermal phenomena, including the thermal radiation from the 21-cm line of neutral hydrogen in the ISM, and the thermal radiation from a wide variety of molecular lines, coming from dense, extremely cold gas concentrations that are found within the ISM. The radio noise discovered by Jansky belongs to an entirely different, non-thermal regime; it comes from charged particles, usually electrons, with very high energies, moving at relativistic velocities in the magnetic fields of the ISM. This regime of *synchrotron* radiation also accounts for the intense radio emission from quasars and other interesting objects in the Universe. Synchrotron radiation, although it can generate radiation up to X-ray and beyond, is a particularly prominent long-wavelength phenomenon, giving radio astronomy a unique role in the investigation of some of the most energetic objects in the Universe.

Radio is uniquely suited to observations of the cosmic microwave background (CMB), which is a black body whose 3 K temperature has a maximum emissivity at wavelengths of order 1–2 mm. Radio observations of the CMB have created a virtually new subject of precision cosmology.

The methods of the radio astronomer often appear to be quite different from those of the optical astronomer, but there is the same aim in all of astronomy, from the radio to the X-ray and gamma-ray domains. Nature presents us with a distribution of brightness on the sky, and it is the task of the astronomer to deduce, from this brightness distribution of electromagnetic radiation, what the radiating sources are, and what physical processes are acting. The distinguishing feature of a radio telescope is that the radiation energy gathered by the instrument is not measured immediately, a process known as *detection* in radio terminology. Instead, the radiation is amplified and manipulated coherently, preserving its wave-like character, before it is finally detected. The instrumental goals of the radio astronomer – obtaining a larger collecting area, greater angular resolution and more sensitive detectors – are otherwise the same as they are for all the astronomical disciplines.

To illustrate the relation between radio and other astronomies, the energy flux of electromagnetic radiation arriving at the Earth's surface from the cosmos is plotted in Figure 1.1. The wavelength scale runs from the standard radio broadcast band to the X-ray region, and the atmospheric windows are indicated schematically. The optical window is seen to be relatively narrow, blocked at the ultraviolet end by ozone absorption and at still shorter wavelengths by oxygen and nitrogen, while at the infrared end the principal absorbing

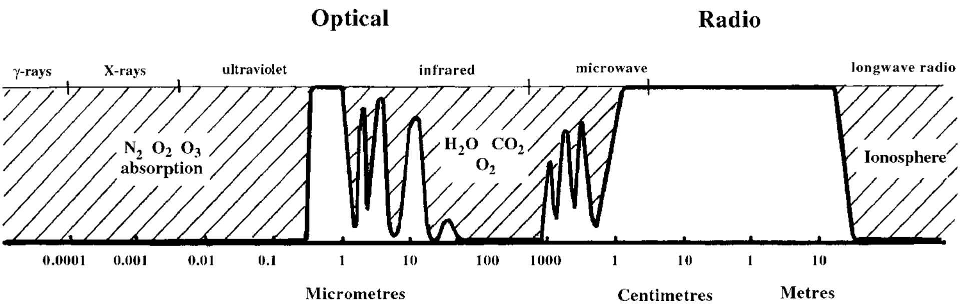

Figure 1.1. The electromagnetic spectrum, showing the wavelength ranges of the 'windows'. The radio range is limited by the ionosphere at wavelengths greater than a few metres. Atmospheric absorption becomes significant in the sub-millimetre range.

agents are water vapour and carbon dioxide. The short-wavelength blockage is so complete that ultraviolet and X-ray work must be carried out above the atmosphere. There are occasional windows in the atmosphere at infrared wavelengths, allowing observations to be made from high, dry mountain sites, but for the most part the observations must be taken from airplanes, balloons or satellites, depending on the particular spectral region. It is easy to see that there is a great stretch of spectrum at the radio end that has relatively little trouble with the atmosphere. Before Jansky's discovery, however, there was no reason to expect much of interest in the radio spectrum; if stars were the principal sources of radiation, very little radio emission could be expected. The maximum radiation from even the coolest of the known stars falls at visible or infrared wavelengths, and their contribution to the radio end of the spectrum is almost negligible. The slow response to Jansky's discovery is understandable both in terms of technical difficulty and lack of expectation.

The radio window is often divided into bands by frequency and wavelength: HF (below 30 MHz), VHF (30–300 MHz), UHF (300–1000 MHz), microwaves (1000–30 000 MHz), millimetre-wave and sub-millimetre-wave. Certain microwave bands have acquired particular names: L-band (≈20 cm), S-band (≈10 cm), C-band(≈6 cm), X-band (≈3 cm), Ku-band (sometimes called U-band, ≈2 cm) and K-band (≈1 cm). The names of the microwave bands are rooted in history, like the s, p, d states of atoms; they are commonly met with in practice.

1.2 Thermal and non-thermal processes

During the pioneering stage of radio astronomy, as a wide range of celestial objects turned out to be detectable in the radio spectrum, two broad classes of emitter became clearly distinguished. At centimetric wavelengths the radio emission from the Sun, as observed by Southworth (see Appendix 3), could be understood as a thermal process, with an associated temperature. The term *temperature* implies that there is some approximation to an equilibrium, or quasi-equilibrium, condition in the emitting medium; in this case the medium is the ionized solar atmosphere. The mechanism of generation is electron–ion collisions, in which the radiation is known as *free–free emission* or *bremsstrahlung*. At metre wavelengths, however, the outbursts of very powerful solar radiation observed by Hey (Appendix 3) could not be understood as the result of an equilibrium process. The distinction was therefore made between *thermal* and *non-thermal* processes, a distinction already familiar in other branches of physics. Many of the most dramatic sources of radio emission, such as the supernova remnants Cassiopeia A and the Crab Nebula, the radio galaxies M87 and Cygnus A, pulsars, and the metre-wave backgrounds from our own Milky Way Galaxy, are non-thermal in nature.

Nevertheless, for practical reasons the term 'temperature' was adopted in a variety of contexts, following practices that had been used widely in physics research during the 1940s. Within a system, individual components can exhibit different temperatures. In a plasma excited by a strong radio-frequency field, for example, the electron and ion components of the gas may each show velocity distributions that can be approximated by Maxwell–Boltzmann distributions, but at quite different temperatures. Each component is in a state of approximate thermal equilibrium, but the systems are weakly coupled and derive their excitation from different energy sources. One can speak, therefore, of two values of *kinetic temperature*, the *electron temperature* and the *ion temperature*.

A two-state system such as the ground state of the hydrogen atom, in which the proton and electron spins can be either parallel or antiparallel, can be used as a simple and illuminating example of how the temperature concept can be generalized. Given an ensemble of identical two-state systems at temperature T_s, the mean relative population of the two states, $\langle n_2/n_1 \rangle$, is given by the Boltzmann distribution

$$\langle n_2/n_1 \rangle = \exp[-\epsilon/(kT_s)], \tag{1.1}$$

where the energy separation ϵ corresponds to a photon energy $h\nu$. If the two states are degenerate, the statistical weights g_1 and g_2 must be applied. The relationship can be inverted, however: for any given average ratio of populations, there is a corresponding value of the temperature, defined by the Boltzmann equation. This defines the *state temperature*, T_s.

The state temperature need not be positive. When $\langle n_2/n_1 \rangle$ is greater than 1, Equation (1.1) requires a negative state temperature, and this is precisely the condition for *maser* or *laser*[1] action to occur. A resonant photon beam traversing a medium at a positive state temperature suffers absorption, whereas it will be amplified if the state temperature is negative. Naturally occurring masers are common in astrophysics, particularly in star-forming regions and in the atmospheres of red giants. These are treated in Chapters 7 and 9. The population inversion is maintained by a pumping mechanism, which can be either radiative or collisional; the action may be to fill the upper state faster than the lower state, or to populate both states, but with the lower state being drained of population more rapidly.

Atomic and molecular systems almost always have a large number of bound states, and one can associate a state temperature with each pair of states. If the system is in a state

[1] These acronyms stand for **M**icrowave (and **L**ight) **A**mplification by the **S**timulated **E**mission of **R**adiation.

of thermal equilibrium, all these temperatures will be the same. The case of blackbody radiation, which is an example of a system with a continuum of energy states, is treated in Chapter 2 and the idea of *brightness temperature* is introduced. In brief, this assigns to an emitter of radiation at frequency ν the temperature that it would have to have if it were a black body. This need not correspond to a physical temperature, and the powerful non-thermal emitters exhibit brightness temperatures that can exceed 10^{12} K. Conversely, a thermal source of radiation need not have a brightness temperature that is constant over a wide spectrum and equal to the physical temperature; the variation of brightness temperature with frequency will be determined by the equation of radiative transfer, introduced in Chapter 7.

The temperature concept is also extended to the practice of receiver measurement. An ideal amplifier should add as little noise as possible to the system, although the laws of quantum mechanics prevent an amplifier from being entirely noise-free. The total excess noise is described as the *system noise temperature*; the definition arises from the properties of a resistor as a noise generator. Every physical resistance generates noise, because of thermal fluctuations in the sea of conduction electrons, and the noise power per unit bandwidth that can be extracted from the resistor is proportional to its temperature. The excess noise observed with any radio-astronomy receiver can be described by stating what temperature a resistive load would have to have, when connected to the input, to generate the observed noise. This turns out to be an entirely practical way to describe the system, because the faint continuum radio signals that one deals with are most conveniently calibrated by using as a reference the continuum noise generated by a hot (or cold) resistive load.

1.3 Radiation processes and radio observations

The use of thermodynamic concepts has more than a formal value. General properties of radiation processes and general theorems about antennas and receivers can be deduced from thermodynamic considerations. In a blackbody enclosure, where the radiation is in equilibrium with all matter in the enclosure, there is no need to specify any details of emission or absorption processes. The best practical example in radio astronomy is the CMB radiation, which at wavelengths shorter than 20 cm becomes the predominant source of the sky brightness (except for a strip about 3 degrees wide along the Galactic plane caused by thermal radiation from the interstellar medium). The CMB is specified completely by the temperature 2.74 K, from which the intensity over a wide range of wavelengths can be calculated. No radiation process need be invoked in the calculation; the radiation was originally in equilibrium with matter in an early stage of cosmic evolution, and has preserved its blackbody spectrum in the subsequent expansion and cooling.

The sky at long radio wavelengths is, however, very much brighter than is expected from the cosmic background alone; its brightness temperature at wavelength 10 m (30 MHz) exceeds 100 000 K. This radiation originates from high-energy electrons circulating in the magnetic field that permeates the interstellar medium in the Galaxy, which radiate predominantly at long wavelengths, with a spectrum that is completely different from that of a black body. This brings in an immediate cross-disciplinary contact with the study of the very energetic cosmic rays, a connection that might have been thought unlikely because of the low energies of radio photons. The relevance of radio observations to high-energy phenomena has continued, since the radio and X-ray observations of active galactic nuclei and quasars have close relationships to one another. One might note that there is a complementarity with optical observations as well; regions of high X-ray and radio luminosity tend to be faint optically, since the effective temperatures are so extreme that the matter is often highly ionized. Nevertheless, the optical observations are essential to understanding what types of object are the sources of emission, and to put the radio observations into a physical and astrophysical context.

Observations do not take place as an abstract process, and the diligent observer will have a knowledge of the characteristics of the instrument that is being used to take the data. With this familiarity, advantage can be taken of new and unexpected uses of an instrument, and caution can be exercised in interpreting data that may contain instrumentally induced flaws. The basic properties of radio telescopes are summarized in Chapter 4, followed by expositions of interferometry and aperture synthesis in Chapters 5 and 6. Both single-aperture telescopes and synthesis arrays are in intensive use, and the language of Fourier transforms is appropriate to both kinds of instrument. It will be obvious that Fourier-transform methods have wide applications to nearly all fields of science and technology, including radiation processes, antenna theory and, especially, aperture-synthesis interferometry. Most readers will be familiar, to a greater or lesser extent, with the Fourier transform; as an aid to the memory, Appendix 1 summarizes its basic properties and applications.

A careful observer will always be aware that the statistical significance of a result must be evaluated. In radio astronomy, one is nearly always looking for signals in the presence of noise, and Chapter 3 gives an exposition of the properties of random noise. Here, too, Fourier methods are essential, both in radiometry and spectroscopy.

The propagation of radio waves through stellar atmospheres, the interstellar medium and the terrestrial atmosphere differs in some important ways from the more familiar optical case. In Chapter 7 we deal with radiative transfer, leading to a brief exposition of maser action, and with the various effects of refraction in the ionized stellar medium. These effects are part of the tools of radio astronomy, giving access to such diverse quantities as the dynamics of gas motions close to an active galactic nucleus and the configuration of the magnetic field of our Galaxy.

Chapters 8–13 show how these various radio techniques have provided new insights into the astrophysics of stellar atmospheres, neutron stars, galaxies and quasars. Observations of the CMB, which is the subject of Chapters 14 and 15, have transformed our understanding of the Universe, and have given access to some of the most fundamental aspects of cosmology. Chapter 16 deals with the population of radio galaxies and quasars within the Universe. Finally, in Chapter 17, we note that radio astronomy is entering a new era in which very large and sensitive radio telescopes are being built as international projects, covering the whole of the radio range from metre to sub-millimetre wavelengths.

2

The nature of the radio signal

All telescopes – radio, optical and X-ray – couple the electromagnetic radiation from sources in the Universe to the astronomer's measuring devices. Spacecraft can explore the solar system directly, but otherwise the Universe is accessible to us only by observing the distribution of electromagnetic radiation across the sky, including its variation with time, frequency and state of polarization. For the radio astronomer, the incoming radiation can be treated as a superposition of classical electromagnetic waves, whereas for the optical or X-ray astronomer, the radiation is arriving as photons, discrete quanta of energy. Infrared astronomy is between these extreme regimes; the 'far' infrared is close to millimetric-wavelength radio in techniques, while the 'near' infrared is regarded as an extension of the optical regime. All astronomical observing starts with the telescope intercepting the incoming electromagnetic radiation. The received radiation goes to a radiometer, followed by a detection apparatus, which may be integral with the radiometer. The principal difference between radio astronomy and astronomy at other wavelengths is the use of low-noise amplifiers prior to signal detection and the consequent possibilities of using signal-processing techniques. The laws of quantum mechanics limit the use of amplifiers at shorter wavelengths in most cases.

This chapter is concerned with the properties of electromagnetic radiation, with an emphasis on fields rather than photons. Radio telescopes are treated in a generic sense, linking engineering and astronomical aspects. One difference in terminology should be noted, because radio telescopes are sometimes called radio antennas. Here, the terms radio telescope and radio antenna will be used interchangeably; in general usage, the term antenna is used when the angle of reception is large, as it is for television antennas. When the angle of reception is small, as it is for steerable paraboloids (which are, indeed, analogous to optical telescopes), they are always called radio telescopes.

2.1 Flux density: the jansky

In this section, monochromatic operation at wavelength λ and corresponding frequency ν is usually assumed. In the real world the astronomer's instrument measures a flux S that is the rate at which energy E crosses area A perpendicular to the direction of propagation:

$$S = (\mathrm{d}E/\mathrm{d}t)/A. \tag{2.1}$$

The incoming flux is distributed over a finite receiving band, and it is usually a function of frequency. For this reason, we introduce the concept of a *spectrum* described by the flux per unit bandwidth S_ν, defined as the *flux density* or *specific flux*. The observed flux is equal to the flux density integrated over the receiving bandwidth:

$$S = \int S_\nu \, \mathrm{d}\nu. \tag{2.2}$$

In later chapters, quantities will be introduced that are functions of more than one variable, but these variables play the role of frequencies. Such a function $Q(\nu_1, \nu_2, \ldots)$ can still be called a spectrum, albeit a multivariate spectrum.

An antenna can be treated either as a receiving device, gathering the incoming radiation field and conducting the electrical signals to the output terminals, or as a transmitting system, launching electromagnetic waves outwards. The two cases are equivalent because of time reversibility: the solutions of Maxwell's equations are valid when time is reversed. As a transmitter the antenna produces a beam of radiation whose solid angle is determined by the size of the aperture: the larger the aperture, the narrower is the beam and the greater is the maximum power flux at the centre of the beam. The concept of the *power gain* of an antenna, which arises in transmission, is therefore closely related to that of *effective area*, which applies to reception.

When a telescope is used in the receiving mode, it is natural to think of it as a receiving area, intercepting a power flux S and yielding a received power P_{rec}. The *effective area* A_{eff} is directionally dependent, and is a function of direction $\hat{\mathbf{a}}$, measured with respect to the antenna axis (generally the direction $\hat{\mathbf{a}}_0$ of maximum response), so that

$$P_{\mathrm{rec}} = A_{\mathrm{eff}} S. \tag{2.3}$$

The range of directions over which the effective area is large is the *antenna beamwidth*; from the laws of diffraction the beamwidth of an antenna with characteristic size d is of order λ/d.

As a transmitter, the same antenna would have a power gain $G(\hat{\mathbf{a}})$ in a direction $\hat{\mathbf{a}}$ that is the ratio of the power flux $S(\hat{\mathbf{a}})$ that would be measured at some large distance and the power flux from a hypothetical isotropic radiator measured at the same distance. For a transmitter power P_{tr}

$$S(\hat{\mathbf{a}}) = \frac{G(\hat{\mathbf{a}})\mathbf{P}_{\mathrm{tr}}}{4\pi r^2}. \tag{2.4}$$

Conservation of energy requires that the integral of $S(\hat{\mathbf{a}})$ over the whole sky, i.e. 4π solid angle, must equal P_{tr}, so that

$$\int_0^{4\pi} G(\hat{\mathbf{a}})\mathrm{d}\Omega = 4\pi. \tag{2.5}$$

Most antennas concentrate the greater part of the radiation into a single principal beam of effective solid angle Ω_0. For order-of-magnitude calculations, therefore, the radiation outside the principal beam is neglected, and the gain in the principal beam can be approximated by

$$G = 4\pi/\Omega_0. \tag{2.6}$$

For a symmetrical aperture having an area of order D^2 the principal beam has a width of order λ/D and solid angle λ^2/D^2. It follows that the effective area $A_{\rm eff}$ is proportional to the gain:

$$A_{\rm eff} = \lambda^2 G/(4\pi). \tag{2.7}$$

This presentation is only illustrative, but the relation is exact, as shown in Section 2.2 below, and holds for both radio and optical telescopes.

The detailed telescope power gain over all angles is known, from radio engineering, as its *polar diagram*. The polar diagram, in addition to having a principal beam, exhibits the complete diffraction pattern, and the response outside the principal beam is referred to as the *sidelobe response*. In optical terminology, the power gain response is usually called the *point-spread function*.

Astronomical sources, both radio and optical, have a finite angular extent, even though they may appear as point sources, and therefore their appearance is characterized by a flux per unit solid angle, called the *brightness*, $B(\theta, \phi)$. Furthermore, the radiated power is a function of frequency, and is designated the *specific brightness* B_ν, which is the flux per unit solid angle per frequency interval:

$$dB_\nu \equiv (dS/d\Omega)d\nu = (dE/d\Omega)dA\,d\nu\,dt. \tag{2.8}$$

Thus the total flux is given by the integral over solid angle and frequency band

$$S = \int\int B_\nu(\theta, \phi)d\Omega\,d\nu. \tag{2.9}$$

The radiative flux per unit solid angle per unit bandwidth is generally designated the *specific intensity* I_ν.

We reserve the term brightness B_ν for the specific intensity at the emitting surface, while I_ν is used for the local value along a ray path, since it may be changed by emission and absorption processes (Chapter 7). In free space, I_ν, or B_ν, is invariant; consequently in the absence of absorption the surface brightness is independent of the distance of the emitting object.

In the radio context mks units are generally used. The *specific power*, or *power density* P_ν, has units of W Hz^{-1}, and the *specific flux*, or *flux density*, S_ν, has units of W m^{-2} Hz^{-1}. A convenient unit of flux density has been designated the *jansky* (Jy):

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

The jansky is also widely used in the infrared spectrum; for example the Spitzer infrared satellite observatory has been calibrated over a wide band of wavelengths in terms of

Table 2.1. *Flux densities of a source with visual magnitude $m_v = 0$*

Band name	Wavelength (μm)	S_ν (Jy)
V (visual)	0.556	3540
J	1.215	1630
H	1.654	1050
K	2.179	655
L	3.547	276
M	4.769	160
N	10.472	35

janskys (Werner 2004). The commonly encountered infrared bands J, H, K, L, M and N are determined by the Earth's atmosphere, which has numerous absorbing bands of water and carbon dioxide that block observations between the bands. The wavelength equivalents of these bands are shown in Table 2.1, which also shows the flux density in these bands for a star with visual magnitude $m_{\mathrm{v}} = 0$.

The magnitude scale of optical astronomy was established in ancient times, and is now defined as a logarithmic scale on which a magnitude difference of 5 corresponds to a factor of 100 in flux ratio. The scale is fixed by measurements of the bright star Vega, an A0 star with a spectrum close to that of a black body. Separate calibrations are necessary for the individual photometric bands conventionally used in optical photometry.[1] The flux densities for the infrared bands in Table 2.1 are quoted in *Astrophysical Quantities* (Allen; 4th edn, 2000) from Cohen *et al.* (1992).

Radio astronomers, following the physicists and electrical engineers who founded the new science, also use a logarithmic scale, the decibel (see Section 3.2), to express the wide range of power encountered in radio engineering, but no decibel scale for fluxes has been adopted.

For historical reasons the calculation of astrophysical radiation processes will be given in cgs units. The necessary conversions between the practical use of mks and the use of cgs units in astrophysics should cause little difficulty.

2.2 Antenna temperature

Figure 2.1 shows a telescope that is enclosed in a black body, an enclosure filled with radiation in thermal equilibrium with the walls of the enclosure, at temperature T. The output terminals of the telescope are connected to a transmission line that in the radio case is usually a coaxial cable or a waveguide. The signal, with or without amplification, passes through a filter that determines the bandwidth B over which the signal is averaged. The

[1] The flux equivalents for commonly used visual bands are presented by Gray (1998); centred on the Johnson and Strömgren V bands at 5480 Å, where the flux of an $m_{\mathrm{v}} = 0$ star is given as $F_\lambda = 3.68 \times 10^9 (5480/\lambda)^2$ erg s^{-1} cm^{-2} Å^{-1}; this is equivalent to 3590 Jy at wavelength 0.556 μm.