1

The Role of Radio Observations in Astronomy

1.1 The Discovery of Cosmic Radio Waves

> 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 only became apparent with the major discoveries in the 1950s and 1960s of the 21 cm hydrogen line, the evolution of distant radio sources, quasars, pulsars, and the cosmic microwave background.

Radio astronomy had revealed a previously unseen Universe and is now one of the prime observational tools available to astronomers. There are several fields of application in which it is especially, sometimes uniquely, useful, as follows.

The cosmic microwave background (CMB) The early Universe is observable as a black body whose ~ 2.7 K temperature has maximum emissivity at millimetre wavelengths.

High energy processes in galaxies and quasars These emit intense radio waves from charged particles, usually electrons, moving at relativistic velocities.

Cosmic magnetic fields These are revealed in radio sources and in interstellar space by the polarization of radio waves.

Astrochemistry Molecular constituents of clouds in the Milky Way and in distant galaxies are observable by radio spectroscopy.

Star and planet formation Condensations of atoms and molecules are mapped by millimetre-wave synthesis arrays.

Kinetics of galaxies Radio spectroscopy, especially of the 21 cm hydrogen line, reveals the dynamic structure of galaxies.

Neutron stars The timing and structure of pulses from pulsars opens a wide field of research, from condensed matter in neutron star interiors to the gravitational interactions of binary star systems.

General relativity Pulsars, the most accurate clocks in the Universe, are used to measure the geometry of space–time.

There are several reasons for radio astronomy's wide and diverse range of astrophysical impact. Radio waves penetrate dust and gas, which absorb and scatter radiation in most other wavebands, allowing us to see into galaxies and molecular clouds. Thermal emission from cold interstellar dust and the free–free emission from hot interstellar plasma are both best seen in radio. Intense non-thermal synchrotron emission is generated by relativistic electrons spiralling around magnetic fields. Synchrotron radiation, although it can be detected up to X-rays 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. Finally, the development of aperture-synthesis imaging provides the means to produce the highest resolution images possible at any wavelength; even the region near the event horizon around the black hole in the centre of the Milky Way is accessible to study.

While in this text we have emphasized the particular contributions of radio astronomy, we stress that in many areas of study astrophysics has become a multiwavelength endeavour. Each regime contributes in its own unique way towards a greater understanding. Thus optically measured redshifts are vital to establish the cosmological distances of active galactic nuclei (AGN) and the components of gravitational lenses, whilst a combination of X-ray, gamma-ray, and radio observations is needed to obtain a coherent picture of AGN.

The importance of a multiwavelength approach is perhaps best exemplified in our own Galaxy, the Milky Way, which is the origin of the radio noise first observed by Jansky. The Galaxy is a complex assembly of stars of widely varying ages, embedded in an *interstellar medium*, or ISM, of ionized and neutral gas, itself displaying a great diversity and complexity throughout the electromagnetic spectrum. Most observations target 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 strong. In contrast, 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 comes from non-thermal synchrotron radiation from very high energy electrons circulating in the magnetic field that permeates the interstellar medium in the Galaxy; its polarization is a tracer of the magnetic fields of the ISM.

The methods of the radio astronomer are often quite different from those in other wavelength regimes. There is a fundamental physical reason for this. Whilst in principle the radio signals gathered by a telescope can be understood as sums of myriad radio quanta, these quanta have the lowest energies of all across the electromagnetic (EM) spectrum (10^{-7} eV at 30 MHz to 10^{-3} eV at 300 GHz). This means that we never have to worry about their quantum statistical properties, and radio signals can be treated as classical waves up to the sub-mm regime (THz frequencies). As a consequence, before their power is measured (*detected* in radio terminology), radio signals can be turned into

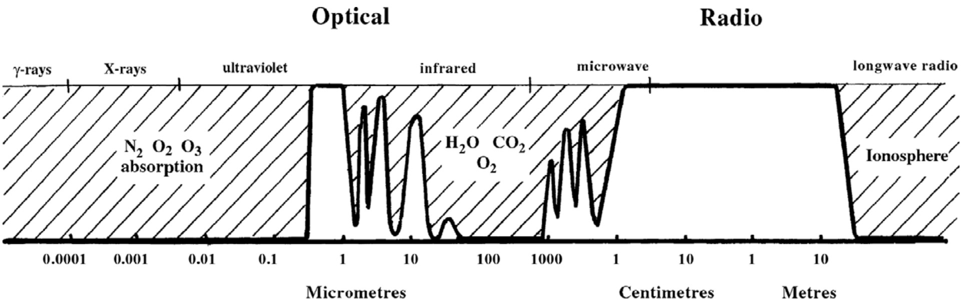

Figure 1.1. The electromagnetic spectrum, showing the wavelength range of the atmospheric ‘windows’. The radio range is limited by the ionosphere at wavelengths greater than a few metres, and by molecular absorption in the sub-millimetre range.

complex voltages in the receiver. These voltages can be coherently manipulated, amplified, and split many ways and their frequencies changed, all the while maintaining the relative phases of the constituent waves.

While the methods may differ there are the same observational aims in the whole of astronomy, from the radio to the X-ray and gamma-ray domains. Nature presents us with a distribution of (frequency-dependent) brightness on the sky, and it is the task of the astronomer to deduce, from this brightness distribution of electromagnetic radiation, what the sources of emission are and what physical processes are acting.

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 AM radio broadcast band (hundreds of metres) to the gamma-ray region. The atmosphere is a barrier to all but two wavelength regions, radio and optical (including the near-infrared). Observations from spacecraft, clear of the atmosphere, now extend over the whole range of wavelengths but are necessarily limited to telescopes with small overall dimensions. The large ground-based telescopes on which radio astronomy depends use the whole of the radio ‘window’, from metre to millimetre wavelengths.

The atmospheric blockage at wavelengths short of the ultraviolet arises from a combination of nuclear interactions and electronic ionization and excitation, principally in ozone, oxygen, and nitrogen molecules. It is so complete that at ultraviolet and shorter wavelengths all observations must be carried out above the atmosphere. The optical–near-infrared window (0.3–1.1 microns) is relatively narrow; within this range the eye’s sensitivity spans an even smaller region, 0.4–0.7 microns. In the infrared the atmospheric absorption arises from quantized vibrational transitions, principally in water vapour and carbon dioxide molecules. There are some atmospheric windows at infrared wavelengths, in particular 8–14 microns, through which the Earth’s surface radiates heat energy into space. As we move into the sub-mm to mm waveband the absorption arises from quantized molecular rotations, and again there are some windows. Infrared and sub-mm observations can be made from high, dry, mountain sites or ultra-cold sites such as the South Pole, but for the most part observations must be taken from aircraft, balloons, or satellites.

Table 1.1. *International frequency band designations; these remain in common use although a simpler A–M naming system covering the range d.c. to 100 GHz is now recommended. P-band (230–470 MHz) is used at the Jansky Very Large Array (JVLA) and the waveguide bands Q (33–50 GHz) and U (40–60 GHz) are also in use.*

Band	Frequency (GHz)
L	1–2
S	2–4
C	4–8
X	8–12
Ku	12–18
K	18–27
Ka	27–40
V	40–75
W	75–110

It is easy to see that there is a great stretch of the spectrum at the radio end (covering four orders of magnitude from millimetre to decametre waves) in which the atmosphere has much less effect. The bottom end is limited by the ionospheric plasma which, although variable, does not usually allow the passage of wavelengths longer than ∼30 metres (10 MHz). Before Jansky's discovery 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 thermal emission from even the coolest of the known stars falls at visible or infrared wavelengths, and their contribution to the radio end of the spectrum was regarded as almost negligible. The slow response to Jansky's discovery is therefore understandable in terms of both technical difficulty and lack of expectation.

The radio spectrum is often described by bands in frequency whose names are rooted in history, like the S, P, D states of atoms. Early names were: HF (high frequency, below 30 MHz); VHF (very high frequency, 30–300 MHz); UHF (ultra high frequency, 300–1000 MHz); microwaves (1000–30 000 MHz); and millimetre waves and sub-millimetre waves beyond that. A commonly used set of names covering the narrower bands is listed in Table 1.1.

1.2 The Origins of Radio Astronomy

The discoveries which opened the window of radio astronomy depended on advances in technique, and most of them arose unexpectedly. Here we summarize the major discoveries which introduced the wide scope of astrophysics to which radio now contributes.

1935 When Karl Jansky, at the Bell Telephone Laboratories, discovered cosmic radio waves, he was investigating the background of sporadic radio noise which might have limited the usefulness of radio communications on what was then an unexplored short-wavelength band. He built a directional array working at 20 metres wavelength (frequency 15 MHz), and identified our Milky Way galaxy as the main source of the background of radio noise. The radiation originates not in the stars but in energetic electrons in the interstellar medium. The detailed structure of this radiation was investigated by large radio telescopes and by the WMAP and Planck satellites (Chapter 17).

1937 Grote Reber built the first reflector radio telescope, with which he mapped radio emission from the Milky Way galaxy (Reber 1944).

1942 The first detection of radio emission from the Sun, by James Hey during World War II, was again a surprise. The strong radio noise which was jamming metre-wavelength radar was found to be associated with sunspots and solar flares. This was emphatically non-thermal; a lower intensity thermal radiation was later found to originate in the solar corona (Chapter 12).

1948 Two of the most powerful discrete radio sources, Taurus A (the Crab Nebula) and Cassiopeia A, were found by John Bolton in Australia and by Martin Ryle and Graham Smith in Cambridge, UK, to be young remnants of supernova explosions (Chapters 13 and 14). Among these, the Crab Nebula has probably been the subject of more papers than any other object in the Milky Way galaxy.

1951 Radio spectroscopy began with the discovery of the 21 centimetre hydrogen line almost simultaneously in the USA, The Netherlands, and Australia. As predicted by Jan Oort and H. van der Hulst, spectroscopy transformed our understanding of the structure of the Milky Way galaxy and eventually of many other distant galaxies. Line radiation from many molecular species has become the new discipline of astrochemistry (Chapter 3).

1954 The development of interferometer techniques, initially in Australia and the UK, led to the accurate location and identification of radio galaxies, such as Cygnus A, at large extragalactic distances. Cygnus A was discovered by Hey in his early survey of the radio sky (Hey *et al.* 1946); its trace can even be discerned on Grote Reber's pioneering 1944 map (Reber 1944). It is, however, an inconspicuous object optically, and it was not identified until its position was known to an accuracy of 1 arcminute (Smith 1952; Baade and Minkowski 1954). A substantial proportion of these extragalactic sources were found later to have very small diameters; these became known as quasars (Chapter 16). The structure of these powerful radio emitters revealed the very energetic processes now known to be due to a black hole, with plasma jets streaming out to huge distances.

1958 The first suggestion that radio astronomy might contribute to cosmology was in 1958, when the large numbers of extragalactic sources discovered in the Cambridge surveys led Martin Ryle to suggest that their statistics appeared to contradict the steady-state cosmological theory. These sources are now numbered in millions, and their evolution traces the phases in the development of the Universe and its contents (Chapter 16).

1962 Interferometer techniques, notably that of aperture synthesis developed by Martin Ryle at Cambridge, and the radio links for long baselines, developed by Henry Palmer at Jodrell Bank, have become the foundations of modern radio telescopes covering the whole available radio spectrum (Chapters 8, 10, and 11). The design of the huge Square Kilometre Array (SKA) is derived directly from these early advances in telescope technology.

1965 The cosmic microwave background (CMB) was discovered by Arno Penzias and Bob Wilson, at the Bell Telephone Laboratories (Chapter 17). Like Jansky, they set out to measure the background against which radio communications must contend, but at the much shorter wavelength of 7.4 centimetres (4.1 GHz). This discovery, with the subsequent detailed evaluation of the structure of the CMB, marks the transformation of cosmology into a precise discipline.

1966 Pulsars were discovered by Jocelyn Bell and Antony Hewish in a survey of discrete radio sources which unusually was deliberately aimed at finding rapid fluctuations. Following the identification of pulsars as neutron stars, which can provide extremely accurate clocks, pulsar research has not only initiated the study of neutron stars, their physics, and their origin, but has provided the most accurate test of general relativity and demonstrated the existence of gravitational waves many years before their direct detection in 2016 (Chapter 15).

These major steps forward depended on the determination of pioneering observers to make the best possible use of the available technology. Receiver sensitivity, angular resolution, frequency coverage, spectral resolution, and time resolution have all achieved orders-of-magnitude improvements between Jansky and the measurement of the CMB structure. Radio telescopes grew, and continue to grow, bringing increased sensitivity and angular resolution. The advent of digital computing allowed the development of aperture synthesis, which led to the Square Kilometre Array, the largest telescope project in any part of the spectrum. There was also an element of good fortune in most of the discoveries listed above, but good fortune often comes to those who are prepared for it in their exploitation of a new technique. There is plenty of scope for new discoveries; the existing telescopes are continually being improved, and the SKA will provide such huge volumes of data that a new approach is already needed to the handling of such a flood of information.

1.3 Thermal and Non-Thermal Radiation Processes

During the pioneering stage of radio astronomy, a wide range of celestial objects turned out to be detectable, and two broad classes of emitter became clearly distinguished. At centimetric wavelengths the radio emission from the Sun 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* (Chapter 2). At metre wavelengths, however, the outbursts of very powerful solar radiation observed by Hey 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. We return to this point later in this section and in Chapter 5.

The archetype of thermal sources is a black body, in which the radiation is in equilibrium with the emitting material, no matter what that is, and there is no need to specify any details of emission or absorption processes. The mathematical form of the spectrum is always the same and its intensity as a function of frequency or wavelength depends only on the temperature. The best example in radio astronomy, and indeed the best known anywhere, is the cosmic microwave background (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 radiation from the interstellar medium). The CMB spectrum is specified (almost) completely by the temperature 2.725 K. As just noted, 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 of the Universe. Thermal emission, being essentially a random process, exhibits no preferred direction at emission and hence is unpolarized. However, polarization can be subsequently imposed during the propagation path, just as sunlight from the sky is polarized by scattering in the Earth's atmosphere. We discuss the polarization of the CMB in Chapter 17.

Within a thermally emitting source, 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 magnetic moments of the proton and electron 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 (atoms or molecules) at temperature T_{s}, the mean relative population of the two states, $\langle n_2/n_1\rangle$, is given by the Boltzmann distribution:

$$\langle n_2/n_1\rangle = \exp(-\epsilon/\mathrm{k}T_{\mathrm{s}}), \tag{1.1}$$

where the energy separation ϵ corresponds to a photon energy $h\nu$. If the two states are degenerate, the statistical weights[1] g_1 and g_2 must be applied. The relationship can be inverted; 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}.

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[1] The number of states which have the same energy.

The state temperature need not be positive. When $\langle n_2/n_1 \rangle$ is greater than 1, Eqn 1.1 requires a negative state temperature, and this is precisely the condition for *maser* or *laser*[2] action to occur. Whereas a beam of photons with energy ϵ traversing a medium at a positive state temperature will suffer absorption, it will be coherently amplified as a result of stimulated emission 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 3 and 13. The non-thermal population inversion is maintained by a pumping mechanism, which can be either radiative or collisional; the action may be either 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 of thermal equilibrium, all these temperatures will be the same. Blackbody radiation is associated with a continuum of energy states.

In Chapter 2 we explain the idea of the *brightness temperature*, mentioned above. 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, and usually does not, correspond to a physical temperature. For example, the sky at long radio wavelengths is far brighter than is expected from the thermal cosmic background at 2.73 K. Instead the Milky Way shines principally by the synchrotron mechanism and its brightness temperature at 10 m wavelength (30 MHz) can exceed 100 000 K (Chapter 14). In the extreme conditions found in quasars and active galactic nuclei, the emission, also boosted by bulk relativistic effects, can exhibit a brightness temperature exceeding 10^{12} K (Chapter 16). Synchrotron-emitting electrons have a distinctly non-Maxwellian energy distribution, which instead takes the form of a power law. As a result the emission spectrum is also a power law, rising towards lower frequencies, completely different from that of a black body. Since synchrotron emission involves a magnetic field, which has a preferred direction in space, the radiation is polarized.

In Chapter 2 we develop the theory behind the radiation mechanisms outlined in this section in more detail. We also introduce the concepts of radiative transfer within an emitting/absorbing medium; this leads to a brief exposition of maser action in Chapter 3, where we discuss the physics of radio spectral lines more generally. The various effects of propagation in the ionized and magnetized stellar medium are introduced in Chapter 4. These effects are 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. We end Chapter 4 by considering the propagation effects in the Earth's atmosphere on the radiation, just before it arrives at the telescope.

1.4 Radio Observations

In Chapter 5 we consider the nature of the radio signal received by our telescopes and recognize that one is nearly always looking for weak signals in the presence of random

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[2] These acronyms stand for Microwave (or Light) Amplification by the Stimulated Emission of Radiation.

noise from other sources. In that chapter we recognize that the use of thermodynamic concepts of temperature has more than a formal value. General features associated with measuring brightness temperatures and general theorems about antennas and receivers can be deduced from thermodynamic considerations.

The principles behind the design of basic types of radio astronomy receivers and how they are calibrated are developed in Chapter 6. The radio emission from many cosmic radio sources contains spectral lines, and may also be polarized. Spectrometers and polarimeters are described in Chapter 7.

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. The same observer will always be aware that the statistical significance of a result must be evaluated. With this familiarity, advantage can be taken of new and unexpected uses of an instrument, while due caution can be exercised in interpreting data that may contain instrumentally induced flaws.

The temperature concept introduced above is 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. In effect the resistor acts like a one-dimensional black body. 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.

The actual radio receiver is but one part of the overall information collection system. The incoming radio energy first has to be collected, the more the better given its ultra-low levels. In Chapter 8 we therefore describe the principles behind single-aperture radio telescopes (including phased arrays), how to characterize their properties, and some practical issues involved with using them.

A large fraction of modern-day radio observations are taken with interferometer arrays of various types; one of the latest being ALMA, with the SKA to follow over the next decade. It is therefore vital for the student of radio astronomy to have a basic understanding of interferometers before moving on to more advanced texts for the subtler details. It is a widespread experience of lecturers that interferometry is the hardest part of any radio astronomy course. We have therefore split our exposition into two chapters. In Chapter 9 we develop the basic ideas and then in Chapter 10 move on to cover the essential details of modern-day interferometric imaging. In these two chapters we take care to differentiate between adding interferometers, such as phased arrays and aperture arrays, introduced in Chapter 8, and correlation interferometers, the dominant type. The SKA will encompass both types. In Chapter 11 we introduce some more advanced techniques of interferometry.

In discussing the principles of radiometric and spectroscopic receivers, of single-aperture telescopes, and of interferometer arrays, understanding the language of Fourier transforms is essential. Fourier transform methods have wide applications to nearly all fields of science and technology, including radiation processes, antenna theory and, especially, aperture-synthesis interferometry. Many readers will be familiar, to a greater or lesser extent, with the Fourier transform; as an aid to the memory, Appendix A1 summarizes its basic properties and some of its radio astronomical applications.

Chapters 12–16 describe how these various radio techniques have provided new insights into the astrophysics of stars, neutron stars, galaxies, and quasars. Observations of the cosmic microwave background (CMB), which is the subject of Chapter 17, have transformed our understanding of the Universe and have given access to some of the most fundamental aspects of cosmology. Chapter 16 also deals with the evolving population of radio galaxies and quasars within the Universe.

The rich history of radio astronomical discovery has, in significant part, set the agenda for astrophysics and cosmology since the 1960s. In recognition, the Nobel Prize in Physics has been awarded to radio astronomers on four occasions: in 1974 to Ryle and Hewish for the development of aperture synthesis and the discovery of pulsars; in 1978 to Penzias and Wilson for the discovery of the CMB; in 1993 to Taylor and Hulse for the indirect detection of gravitational radiation from a binary pulsar; in 2006 to Mather and Smoot for measurements of the spectrum and anisotropy of the CMB. We can be confident that these will not be the last.

1.5 The Challenge of Manmade Radio Signals

The principal challenge to all radio astronomical observations is that natural sources of radiation produce very weak signals, even from the most powerful cosmic sources and using the largest radio telescopes. For example, consider a radio observation of the supernova remnant Cassiopeia A (Cas A), the strongest radio source in the sky apart from the Sun. Now ask: what would be the energy collected by the 76 m Lovell Telescope (LT) at the Jodrell Bank Observatory (UK) over its entire operational lifetime if it had been pointed continuously at Cas A? Let our virtual observations occupy the long-term protected band 1400–1427 MHz around the 21 cm atomic hydrogen line. The calculation is then straightforward. The flux density (see Chapter 5) of Cas A at 1400 MHz is $\sim 2 \times 10^{-23}$ W m^{-2} Hz^{-1}, thus, multiplying by the 2700 m^2 effective area of the LT (its geometrical area with a 60% aperture efficiency) and the 27 MHz bandwidth gives a rate of energy collection of $\sim 1.5 \times 10^{-12}$ W. Now multiplying by the number of seconds ($\sim 2 \times 10^9$) since the LT was commissioned in 1957 we obtain the total energy collected. The answer is 3×10^{-3} joules, which is the same as that required to power a hand-torch bulb (3 V; 0.5 A) for 2 milliseconds!

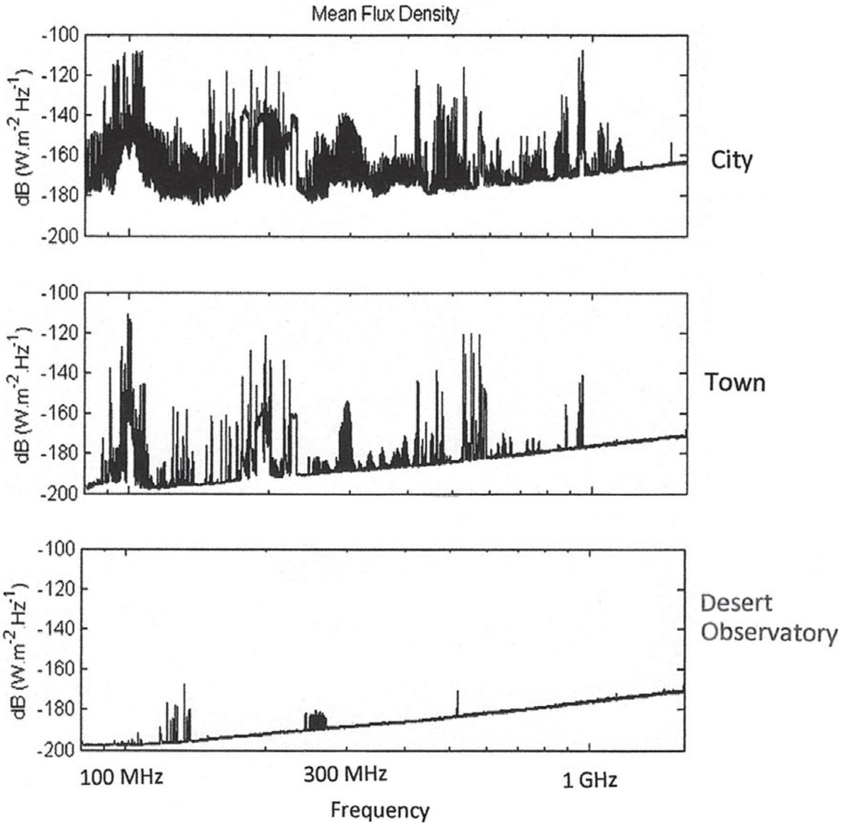

Figure 1.2. The radio frequency spectrum in sites of different population density. Top to bottom: city, town, desert.

Nevertheless, with modern low-noise amplifiers and high-gain but very stable receivers based on solid state devices, the ultra-low power levels associated with a wide range of cosmic radio sources are measured routinely. Early radio astronomers did not have these technological advantages. Their receivers used thermionic devices producing much higher intrinsic noise levels and suffering larger gain variations against which the natural signals had to be discerned. The origins and development of the subject need to be understood in this light.

The radio pioneers had one major advantage over their successors – the low occupation of the radio spectrum by manmade signals. The overriding challenge of present-day radio astronomy comes from the fact that most modern communication systems depend on radio transmissions; as a result the 'interference-free' space for radio astronomical observations is becoming ever more limited. Figure 1.2 illustrates the problem well. It shows the radio frequency spectrum, from $\sim$ 10 MHz to above 1 GHz, in sites of different population density: in a city, a town, and a desert location. These spectra immediately make clear why the current generation of telescopes, built many decades ago in more or less convenient locations, have to operate in non-ideal environments and why the next-generation radio telescopes must be sited in remote regions well away from people. The Square Kilometre Array will therefore be built in the deserts of Australia and South Africa.

Figure 1.2 also shows just how powerful manmade signals are compared with natural ones. The strongest signals reach 10^{-11} W m^{-2} Hz^{-1} and hence are a million million times greater than those from the strong radio source Cas A. Sharing the spectrum between these ever-growing commercial transmissions and radio astronomy is a major task recognized by the International Astronomical Union (IAU) and the International Scientific Radio Union (URSI), working through the International Telecommunications Union (ITU), the body that allocates specific bands of the spectrum to the many and various users.[3] Parts of the spectrum are protected from powerful transmissions such as television, radio broadcasts, and radar; mobile phones, by using cellular networks, are confined to remarkably narrow bands. Satellite networks, particularly navigation systems (GPS, Glonass, Galileo), cannot be avoided anywhere in the world. One of the best protected radio astronomy bands is 1400 to 1427 MHz, covering the 21 cm hydrogen spectral line. Other bands are allocated with various degrees of protection at approximately octave intervals throughout the whole radio window shown in Figure 1.1.

There are, however, large advantages in using the much wider bandwidths provided by modern receiver techniques. In such wide bands unwanted signals, known as radio frequency interference (RFI), are inevitably picked up along with the wanted signals, and must be recognized and rejected. This is achieved by splitting the receiver band into thousands of separate channels, and rejecting those containing RFI. Interferometer techniques are also helpful, especially when the elementary radio antennas are sited far apart and are subject to different, uncorrelated, RFI. The narrower, specifically allocated, bands remain vitally important, especially for the most precise measurements.

1.6 Further Reading

Supplementary Material at www.cambridge.org/ira4.

Graham-Smith, F. 2014. *Unseen Cosmos*. Oxford University Press. A general account of radio astronomy.

Longair, M. 2006. *The Cosmic Century*. Cambridge University Press. A comprehensive history of astronomy up to 2000.

Sullivan, W. T. 2009. *Cosmic Noise*. Cambridge University Press. A history of early radio astronomy.

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[3] The case for protection is made in Europe and South Africa by a joint Committee for Radio Astronomy Frequencies (CRAF); the corresponding body in the Americas is the Committee on Radio Frequencies (CORF) and in the Asia–Pacific region the Radio Astronomy Frequency Committee for the Asia–Pacific Region (RAFCAP).