Radio Astronomy

KRAUS

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With a chapter on Radio-Telescope Receivers by
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Preface

Radio astronomy embraces a wide range of topics from astrophysical phenomena to receiver and antenna design. The aim of this book is to bring together a balanced selection and treatment of these topics that is elementary enough to serve as an introduction to radio astronomy yet is sufficiently detailed to be useful as a teaching text and reference work.

Chapters 3, 4, and 5 cover topics, such as radiation laws and wave polarization and propagation, that are fundamental to radio astronomy. These are followed by Chapters 6 and 7 on antennas and receivers. Chapter 8, which is the final and longest chapter, deals with radio sources and our present state of knowledge concerning them as deduced from both radio and optical observations.

The relation of radio astronomy to other techniques for the exploration of space is discussed in Chapter 1, which also includes a brief history of the early years of radio astronomy. Chapter 2 brings together a variety of astronomy fundamentals that may be useful to those who do not have an astronomical background. There are extensive tables throughout the book of important parameters, formulas, and objects. The appendix includes several lists of radio sources.

Except for Chapter 7, the book is an outgrowth of lecture material presented by the author in courses on radio astronomy and related topics at the Ohio State University over a period of years. Much of the material is suitable for use at the last years of undergraduate or first year of graduate level. As preparation it is desirable that a student have a knowledge of vector analysis and of elementary electromagnetic and circuit theory. Numerous references to the literature and very extensive bibliographies are given to facilitate further study of a particular subject. There are many worked examples. These are supplemented by extensive problem sets having a considerable range in difficulty. Some problems serve to illustrate points not covered in the text. Answers to most of the problems are included.

For the most part the rationalized mks system of units is employed, but in a few cases other systems are used where they are more convenient or appropriate. The meaning and units attached to symbols are explicitly detailed following key equations throughout the book.

The book has dozens of tables, over 100 problems, over 300 figures, and over 500 references. In the appendix there are lists of over 1,000 radio sources.

I wish to express my appreciation to my colleagues and students for helpful comments and suggestions. In particular I should like to thank Prof. Robert G. Kouyoumjian of the Ohio State University, who gave very valuable assistance on Chapter 5. Useful suggestions on individual chapters or parts of chapters were made by Profs. W. K. Bonsack, G. W. Collins II, H. C. Ko, D. S. Mathewson, and T. K. Menon of the Ohio State University Departments of Astronomy and Electrical Engineering and P. N. Myers and S. R. O'Donnell of the Ohio State University Radio Observatory staff. Also Professors Ko and Menon have supplied the basis for several problems. The official U.S. Navy photographs of several

astronomical objects, kindly supplied by Dr. K. Aa. Strand, were taken with the 61-inch astrometric reflector at the U.S. Naval Observatory, Flagstaff, Arizona. The photographs showing Cygnus A and Centaurus A were kindly provided by Dr. Thomas A. Matthews of the California Institute of Technology.

Professor Martti E. Tiuri of the Finland Institute of Technology, who wrote Chapter 7 on radio-telescope receivers, was a visiting professor at the Ohio State University Radio Observatory during 1961–1962. I have edited Dr. Tiuri's manuscript to make the symbols and terminology consistent with those used in the rest of the book, and any errors in his chapter are my responsibility.

Although great care has been exercised, some errors in the text, tables, lists, or figures will inevitably occur. Anyone finding them will do me a great service by writing me about them so that they can be corrected in subsequent printings.

John D. Kraus

Contents

1 Introduction

1-1 Radio Astronomy and the Exploration of the Universe Until a few decades ago man's knowledge of the universe outside the earth came almost entirely from optical-astronomy observations. Beginning millenniums ago with purely visual techniques, astronomy made rapid advances after the invention of the optical telescope in the early seventeenth century and the application of photographic methods in the last century. All observations were in the visible part of the electromagnetic spectrum in a band about one octave wide. During the last three decades astronomical observations at radio wavelengths have created a new branch of astronomy called *radio astronomy.* The older astronomy in the visible spectrum is now often called *optical astronomy* to distinguish it from the newer branch.

The positions of optical and radio astronomy in the electromagnetic spectrum coincide with the two principal transparent bands of the earth's atmosphere and ionosphere. These transparent bands are commonly referred to as the optical and radio windows. A graph of the relative transparency of the earth's atmosphere is presented in Fig. 1-1, with transparency as ordinate ranging from 0 (opaque) to 1 (perfectly transparent) as a function of wavelength on a logarithmic scale. The optical window extends from about 0.4 to 0.8 micron (1 octave) while the much broader radio window extends from about 1 cm to 10 m (about 10 octaves). The values of 1 cm and 10 m are nominal and arbitrary. Because of some relatively transparent bands in the millimeter region and occasional ionospheric "holes" at decameter wavelengths, more extreme limits of the radio window may be placed at 1 mm and 150 m. The short-wavelength limit is a function of the atmospheric composition, cloud cover, etc., while the long-wavelength limit depends on the electron density in the ionosphere. This, in turn, is a function of the time of day, solar activity, etc.

The division of astronomy into two branches, optical and radio, is a consequence of the fact that almost all observations to date have been ground-based, with the earth's atmosphere interposed between the celestial source and the observer. With the advent of artificial earth satellites, from simple instrumented types to complex, manned space stations, it is becoming possible to conduct astronomical observations above the atmosphere (Liller, 1961; Kraushaar and Clark, 1962). The National Aeronautics and Space Administration has extensive programs under way for orbiting solar observatories (OSO) and orbiting astronomical observatories (OAO). In the near future, astronomical observations may be made over the complete range of the electromagnetic spectrum from the shortest gamma rays to the longest radio waves. The different techniques needed to cover this broad spectrum will result in the development of special orbiting telescopes for gamma rays, X rays, ultraviolet rays, infrared rays, and radio waves (particularly at the lower radio frequencies cut off by the ionosphere). Current observations from rockets and high-altitude balloons form an important prelude to this bridging of the gaps in the spectrum (Friedman, 1959; Liller, 1961).

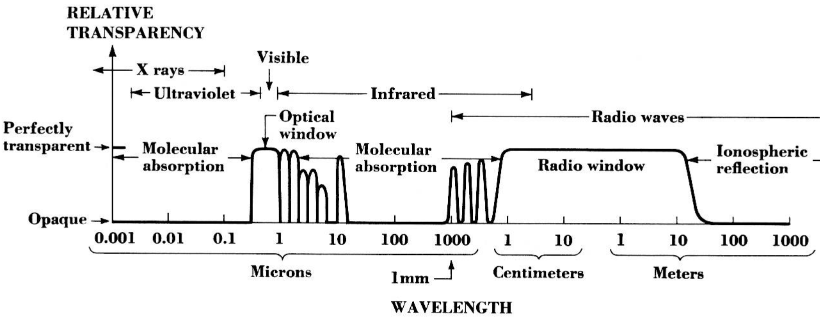

Fig. 1-1. Electromagnetic spectrum showing relative transparency of the earth's atmosphere and ionosphere.

Since all electromagnetic-wave energy is conveyed by photons, the new astronomy embracing the full electromagnetic spectrum may be described collectively as *photon astronomy.* The highest-frequency gamma rays have photon energies of a billion electron volts. On the other hand, a 1-kc radio wave has a photon energy of only a few micromicro electron volts. The range in energy, or frequency, between these extremes is about 10^{20}. This range is so large that widely different techniques will be required in different parts of the spectrum, and it is likely that the techniques in the radio part of the spectrum will continue to be distinctive, with such specialized components as antennas, wave guides, and superheterodyne receivers. Although the various parts of the spectrum may have very dissimilar techniques, the observational data gathered from photons of all energies will form a unified result.

Even at the radio frequencies for which the atmosphere and ionosphere are essentially transparent, there may be important advantages for a space observatory since absorption, refraction, and noise effects will be less.

Another reason is that interference from terrestrial radio transmitters may be reduced. At present, the invasion of more and more channels by larger numbers of higher-powered transmitters seriously threatens the future of ground-based radio astronomy. Although some ground-based radio astronomy may continue to be possible in spite of such interference, it may be necessary for ultimate sensitivity to place radio telescopes in space stations orbiting the earth or to seek even quieter locations, such as may be provided by a lunar-based observatory on the back side of the moon. In choosing an interference-free site, consideration must also be given to the powerful radio emissions from the sun. To radio astronomers not interested in studying these emissions, the sun can be a troublesome source of interference, making nighttime observations necessary or desirable. To reduce such interference a radio telescope in space would require special shielding and other precautions, and even so, the ultimate sensitivity might be achieved only when the telescope was in the shadow of the earth or the moon. The best prospects for avoiding both terrestrial and solar interference would appear to be provided by a lunar-based radio telescope situated on the back side of the moon and operating during the lunar night. But at kilometer wavelengths even such a location may be unsuitable and a site on one of the asteroids may be indicated (Reber, 1964).

So far only a *passive* astronomy, in which celestial objects are studied by means of their natural radiation, has been considered. In recent years, an *active* phase of astronomy has been developed using radar techniques. Here the radiations are man-generated. Radio echoes of signals from powerful terrestrial transmitters have been bounced off the moon, the sun, and several planets. Laser-generated infrared rays have also been reflected back to earth from the moon. However, the time interval required for the waves to make the round-trip journey and the fact that the echo power decreases as the fourth power of the distance impose limitations on the practical range of the radar method. Nevertheless, it is now a powerful technique for studies within the solar system, and its capabilities and importance in this realm will undoubtedly grow (Goldstein, 1964; James, 1964).

Besides emitting photons of electromagnetic energy, celestial objects may radiate in other ways. For example, a massive double-star system sends out gravity waves. It is presumed that gravitational energy, like electromagnetic energy, is quantized and that the carriers, called gravitons, travel with the speed of light. Devices for detecting gravitons are under development (Weber, 1960, 1961). If gravity-wave detection proves feasible, a new branch of astronomy may develop. Since gravitons and photons are both bosons, gravity-wave (or graviton) astronomy and electromagnetic-wave (or photon) astronomy may both be grouped as branches of boson astronomy, as suggested in Fig. 1-2.

This chart also lists other present and future techniques for space exploration. Thus, acoustic waves or magnetohydrodynamic waves generated near the sun's surface can propagate to the earth through the sun's outer corona. This tenuous medium is a gaseous envelope which extends beyond the earth, and observations of mechanical vibrations or motions of the acoustic, magnetohydrodynamic, or other type traveling through it may be regarded as constituting a *pneumatic astronomy,* as suggested in Fig. 1-2.

- **Boson astronomy**
  - **Photon astronomy (passive and active)**
    - **Radio waves**
    - **Infrared rays**
    - **Optical rays**
    - **Ultraviolet rays**
    - **X rays**
    - **Gamma rays**
  - **Graviton astronomy** — **Gravity waves**
- **Pneumatic astronomy**
  - **Acoustic waves**
  - **Magnetohydrodynamic waves**
- **Particle astronomy**
  - **Atomic (microscopic) particles**
    - **Fermions**
      - **Neutrinos**
      - **Electrons**
      - **Protons**
    - **Heavy particles**
    - (Electrons, Protons, Heavy particles) **Cosmic rays**
  - **Macroscopic particles or objects** — **Meteors, meteorites, meteoric dust**
- **Direct techniques**
  - **Space probes**
  - **Manned exploration**

Fig. 1-2. Present and future techniques of space exploration classified into several "astronomies."

Another technique of space exploration or astronomical investigation relies on observations of atomic particles which stream toward the earth in huge numbers from different directions. They include elementary particles such as electrons and protons and heavier, more complex atomic particles. The more energetic of these particles are frequently referred to as *cosmic rays.* Being charged particles, they are deflected by the earth's magnetic field and interstellar fields, so that their direction of origin is difficult to determine. However, some appear to originate on the sun and others from objects, like the Crab nebula, which are also strong radio sources. By studying only cosmic rays of very high energy (about 10^{18} ev) the effect of deflection by the magnetic field is minimized (Rossi, 1959).

Yet another elementary particle with potential for studies of our universe is the neutrino (Chiu and Stabler, 1961). Having no charge, this particle is not deflected by magnetic fields, so that it may travel directly from its point of origin. But the detection of such a neutral virtually massless particle is a formidable problem. Nevertheless, pioneering attempts are in progress to map the neutrino radiation from space (Morrison, 1962).

Neutrinos, electrons, and protons, or collectively fermions, and the heavier atomic particles may be regarded as the carriers for a branch of space exploration called *particle astronomy*. Macroscopic particles, such as meteors, could also be included as a subdivision of this branch, as suggested in Fig. 1-2. Although the groupings in Fig. 1-2 may be convenient, the techniques for detecting the different carriers will vary greatly.

After a meteor falls to the earth's surface it is termed a meteorite. Such objects can be handled and subjected to laboratory tests and analyses. Meteoric dust brought to earth by rain or snow can be studied in the same way. The difference here is that these particles or objects can be examined and reexamined in a leisurely way. They are not so transient as individual photons or fermions.

With the development of artificial satellites and space probes the way has been opened for a more direct approach to many phases of extraterrestrial exploration. Such probes can transport sensing devices for on-the-spot measurements at distant locations and telemeter their findings back to earth. But a human being's capacity for observation and interpretation of diverse and unexpected phenomena will make manned exploration the ultimate in space exploration. As suggested in Fig. 1-2, probes and manned exploration can be grouped together under the heading of *direct techniques*, in contrast to the indirect methods involving observations at a distance by boson or particle astronomy.

The classification of techniques in Fig. 1-2 is not intended to be complete in all respects. Thus, only a few fundamental particles have been listed, and no attempt has been made to include any antiparticles. The classification, like any such scheme, is also quite arbitrary and groupings could be made into different "astronomies." The principal purpose of Fig. 1-2 is to place radio astronomy in perspective in relation to other present and future techniques of space exploration.

The difficulties and high cost of exploration by probes and man tend to limit the range of such sorties. Ultimately the solar system may be spanned but the jump of several light years to the nearest stars puts the use of direct techniques for exploration beyond the planets into the distant future, if, indeed, trips to the stars are ever possible at all (Purcell, 1963).

As in the past, the indirect, at-a-distance techniques will continue to be the only ones available for studying the more remote parts of our universe. The very small prospective range of probes and manned space travel compared to radio and optical astronomy is illustrated by the six sketches of Fig. 2-8. Whereas radio and optical telescopes can penetrate far out in the sixth sketch to 5,000 mega-light-years or more, man has not yet covered the interval in the first sketch (1 light-second), and probes have functioned only to the inner parts of the second sketch (1 light-hour).

The objects at the greatest measured distances (5×10^9 light-years) are relatively strong when radio techniques are used but faint optically. It is likely that many of the weaker radio sources are still further away, perhaps near the limits of the universe and beyond the range of optical telescopes. Radio photons are of much lower energy than optical photons and hence are emitted in larger numbers for the same energy radiated. Accordingly, radio astronomy has a fundamental advantage over optical astronomy, or any other photon astronomy, in the detection of distant objects because it has the least tendency to be photon-limited, i.e., have insufficient photons for significant measurements (von Hoerner, 1964). Thus, radio astronomy is not only the most promising technique currently available for studying the most distant parts of the universe but it may be the only one. The potential range of neutrino and graviton techniques is still a question for the future.

Observations at the greatest possible distance are essential to an understanding of both the origin and type of universe in which we live. And this knowledge, in turn, may give some clue as to its ultimate destiny.

1-2 A Short History of the Early Years of Radio Astronomy† The science of radio astronomy had its beginnings in the experiments of Karl G. Jansky in 1931. Jansky was a radio engineer at the Holmdel, New Jersey, field site of the Bell Telephone Laboratories. He had been assigned the problem of studying the direction of arrival of thunderstorm static. This information would be useful since, if a predominant direction was found, beam antennas for transoceanic radio-telephone circuits might be designed to give a minimum response in this direction, thereby improving the signal-to-noise ratio for the circuit. To study the problem Jansky built a vertically polarized unidirectional beam antenna of the Bruce curtain type, as shown in Fig. 1-3. The antenna, about 100 ft long by 12 ft high, was mounted on four wheels running on a circular horizontal track so that the antenna could rotate in azimuth. A synchronous motor turned the structure one revolution every 20 min. Operating at a wavelength of 14.6 m

† A more complete history of radio astronomy replete with personal anecdotes will be found in Pfeiffer (1956); see also Southworth (1956).