RADIOASTRONOMY

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Contents

Summary

This chapter is intended to give the reader an introduction to the science of Radioastronomy. Several topics are outlined starting from the first detection of radio waves from celestial bodies and continuing with the instruments necessary to reveal such emission. Radioastronomy is conducted using large radio antennas referred to as radiotelescopes that are either used singularly, or with multiple linked telescopes utilizing the techniques of radio interferometry and aperture synthesis.

The use of interferometry allows radioastronomers to achieve very high angular resolution, as the resolving power of an interferometer is set by the distance between its elements, rather than the size of its elements. The Very Long Baseline Interferometry (VLBI) technique is described in detail, including space VLBI. The large distances between the telescopes enable the highest angular resolutions to be achieved, much greater in fact than in any other field of astronomy. At the highest frequencies, synthesized beams less than 1 milli-arc second are possible. The last part of this chapter deals with the scientific results obtained since when Karl Jansky first detected radioemission from the Milky Way in the 1930s. Radioastronomy has led to substantial increases in astronomical knowledge, particularly with the discovery of several classes of new objects, including pulsars, quasars and radiogalaxies. This is because radioastronomy allows us to see things that are not detectable in optical astronomy. Such objects demonstrate some of the most extreme and energetic physical processes in the universe.

1. An Invisible Universe

We see the world around us because our eyes are sensitive to the visible light. Visible light is the most familiar form of electromagnetic radiation and covers only a small part of the range of wavelengths in which electromagnetic waves can be produced. An electromagnetic wave is composed of an electric field and a magnetic field that are oscillating together. The fields are oriented perpendicular to each other, and the wave travels in a direction perpendicular to both of the fields. These waves can also be thought of as particles called photons: mass-less packets of energy that travel at the speed of light. In fact, the electromagnetic radiation behaves as both a particle and a wave at the same time. Electromagnetic waves can be characterized by any of three properties: wavelength (λ) - the distance between two adjacent crests of the wave, frequency (f) - the number of wave oscillations per second, or the energy (E) of the individual photons in the wave. For all types of electromagnetic radiation, the simple relationships between wavelength, frequency, and energy are:

$$\lambda = c / f = hc / E$$

In the CGS system of units the wavelength λ λ is measured in cm, the speed of light c is about 3×10^{10} cm s^{-1}, the frequency f is measured in Hertz (Hz, where 1 Hz = 1 wave crest per second; e.g. 1 MHz = 10^6 Hz, 1 GHz = 10^9 Hz), the energy E is in erg, and h is the Planck’s constant, which is equal to 6.63×10^{-27} erg s. All forms of electromagnetic radiation (visible light, X-rays, radio waves, etc.) travel at the speed of light, regardless of their energy. Since the energy of an electromagnetic wave is directly proportional to its frequency and inversely proportional to its wavelength, the higher the energy of the wave, the higher the frequency, and the shorter the wavelength.

We know that objects both on Earth and in space emit other types of electromagnetic radiation that are not visible to us. For example we know about the waves used in radio and television, in mobile phones, in remote control devices, or those radiations considered necessary in medicine and especially in orthopedic and dental medicine, and so on. The electromagnetic spectrum is the range of all possible frequencies of electromagnetic radiation present in nature and extends from low frequencies, used for modern radio communication, to gamma radiation at the short-wavelength end (high-frequency), thereby covering wavelengths from thousands of kilometers down to a fraction of the size of an atom (see Figure 1).

Modern astrophysics studies the Universe using radiations emitted by celestial bodies at all wavelengths and thus not only the visible light but also radio, microwave, infrared radiation, ultraviolet light, the X-rays, the gamma rays, etc. Earth’s atmosphere acts as an opaque barrier to much of the electromagnetic spectrum. We can observe celestial bodies with Earth-bound instruments only in the optical and radio bands. The atmosphere absorbs all of the wavelengths shorter than ultraviolet, most of the wavelengths between infrared and microwaves, and most of the longest radio waves. For radio astronomers this leaves only short radio waves to penetrate the atmosphere and bring information about the universe to our ground based instruments. The main frequency range that passes through the atmosphere is referred to as the radio window.

The radio window consists of frequencies that range from about 10 MHz (10^7 Hertz) to 100 GHz (100×10^9 Hertz). The low-frequency end of the window is limited by signals being reflected by the ionosphere back into space, while the upper limit is caused by absorption of the radio waves by water vapor and carbon dioxide in the troposphere. As atmospheric conditions change the radio window can expand or shrink.

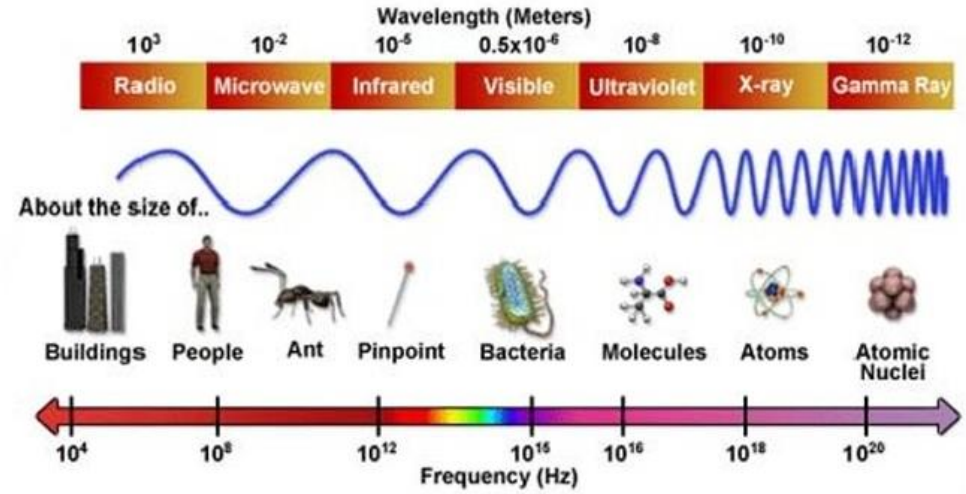

Figure 1. The Electromagnetic Spectrum. (Credit: Magnet Lab, http://www.magnet.fsu.edu).

Radioastronomy studies a Universe not visible to the human eye. In this respect radio astronomical studies have been pioneers in the revelation of the invisible Universe producing a vision completely new of celestial bodies already known, like galaxies, and revealing new objects like pulsars and quasars and radiogalaxies. The emitting region of a radiogalaxy is about a 10^6 times smaller than a normal galaxy due to the existence of a black hole having a giant mass. The power emitted is non-thermal – i.e. it is not due to stellar emission – but it is produced by the motion of relativistic electrons (that is, electrons moving at speeds close to that of light) in a very strong magnetic field (see Sections 4.1 and 4.2). These electrons emit a so-called "synchrotron" radiation when they are spiraling in the magnetic field. It is thought that in the nucleus of radiogalaxies there exists a mechanism able to expel jets of matter and to produce strong magnetic fields. These jets of plasma, after traveling thousands of light years, interact with the intergalactic medium and slow down, thus forming the characteristic lobe structures of the radiogalaxies. High resolution investigations have also revealed a compact radio source, coincident with the galactic nucleus, which is the location of the central engine which feeds the full radiogalaxy: supermassive black hole.

One example of radiogalaxy is Cygnus A (also called 3C 405), the most powerful radiogalaxy in the sky that is located at a distance of 750 million light years from us. Figure 2 illustrates Cygnus A observed at optical and radio wavelengths. The image to the left is an optical image (in negative), as it would appear looking at the radiogalaxy with an optical telescope. Cygnus A is the diffuse galaxy at the center of the image. The radioemission of the same galaxy, shown in the middle and still in negative, extends well outside the optical region and is due to material expelled at relativistic velocity from the central giant black hole. Panel to the right of Figure 2 represents a scaled superposition of the two previous images this time in positive: in red one can see the radiogalaxy and in bluish the optical image of the same region with the diffuse galaxy at the center.

Figure 2. (Left) Optical image of the radiogalaxy Cygnus A as it would appear looking at it with an optical telescope [1]; (middle) radio image of the same galaxy, the central point-like source corresponds to the position of the optical galaxy to the left [2]; (right) radio image of Cygnus A in red, over posed onto the optical image of the radiogalaxy to the left in bluish. (Adapted from http://spider.seds.org/spider/Misc/Pics/).

Both radiogalaxies and quasars are at such large cosmological distances that their radio signals, which arrive on Earth, are extremely weak, from one million to one billion times weaker than those used in communication systems. Because the cosmic radiosources are so weak, they are easily masked by man-made interference. Possibly even worse than complete masking, weaker interfering signals can contaminate the data collected by radiotelescopes. By international agreement certain frequencies have been allocated strictly for radioastronomy. However, in some countries the restrictions are not enforced. Not only, there is also disagreement about the acceptable "spillover" beyond the restricted limits, thus interference represents a problem for radioastronomers.

2. The First Radio Astronomical Observations

Many astronomical objects emit radio waves but that fact was not discovered until the beginning of the 1930s. Before then neither anyone knew that radio frequency radiation is also emitted by billions of extraterrestrial sources, nor that some of these frequencies pass through Earth’s atmosphere right into our domain on the ground. The Bell Lab radio engineer Karl Jansky, who detected cosmic radio noise from near the center of the Milky Way Galaxy, made the first radioastronomy observations in 1932. He built an antenna that was mounted on a turntable that allowed it to rotate in any direction so to earn the name of merry-go-round. By rotating the antenna, one could find what the direction was to any radio signal (see Figure 3).

Jansky was investigating radio disturbance interfering with transoceanic telephone service. After recording signals from all directions for several months, Jansky identified three types of statics. The first two were thunderstorms, both nearby and distant. The third one was a faint steady hiss of unknown origin. As it often happens in science, the discovery of radio frequency radiation from outer space happened while looking for something else. At the beginning Jansky thought he was seeing radiation from the Sun. But after a few months of following the signal, the brightest point moved away from the position of the Sun. He eventually figured out that the radiation was coming from the Milky Way and was strongest in the direction of the center of our Milky Way Galaxy, in the constellation of the Sagittarius. He had discovered the first celestial radio signals! Jansky published findings that were widely publicized and appeared in the New York Times of May 5, 1933 but this discovery did not get the attention it deserved right away.

A few years later, Grote Reber, an amateur astronomer and also a radio engineer, built the first prototype radiotelescope in his backyard in Illinois (Figure 4). In 1938 Reber was successful in detecting radio emission from the center of the Milky Way thus confirming Janskys discovery. In the years from 1938 to 1943, Reber made the first surveys of radio waves from the sky and published his results both in engineering and astronomy journals. By 1944 the first radio frequency sky maps were published.

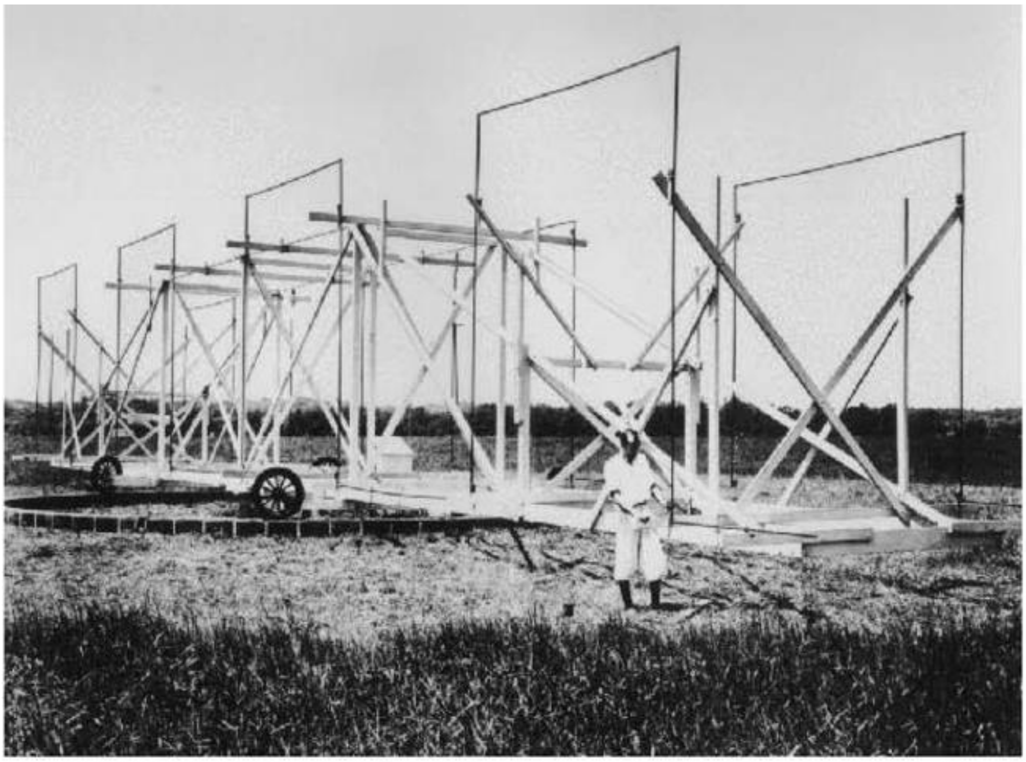

Figure 3. Jansky radio antenna in Holmdel, New Jersey, 1930. (Image courtesy of NRAO).

Reber accomplishments insured that radioastronomy became a major field of research following World War II. Australian and British radio scientists were able to locate a number of discrete sources of celestial radio emission that they associated with old supernovae and active galaxies, which became later to be known as radiogalaxies.

The construction of larger and larger antennas and radio interferometers was complemented by improved radio receivers and processing methods. Since then astronomers have developed sophisticated systems that have allowed them to study fainter radiosources with increased resolution and image quality.

Figure 4. Reber radiotelescope in Wheaton, Illinois, in 1937. (Credit: Emilio Segre Visual Archives/American Institute of Physics/Science Photo Library).

3. Radiotelescopes

Radio waves ranging from wavelengths of a few millimeters to nearly 100 meters can pass through the Earth's atmosphere and produce no effect on the human eye or a photographic plate. They do however produce a very weak electrical current in a conductor like an antenna. Most radio antennas are dish-shaped reflectors that gather the radiation and reflect it to a central focus. The weak current at the focus of the antenna can be amplified by a radio receiver in order to be measured and recorded (see Figure 5).

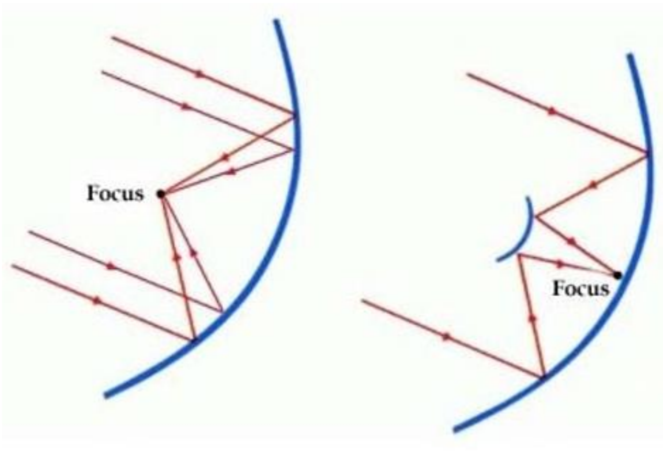

Figure 5. The electromagnetic radiation coming from an object in the sky is reflected by the surface towards the primary focus (on the left), where a detector can be placed. If a second "mirror" is placed in the focus, the radiation reaches the secondary focus (on the right), where it is easier to place the measuring instruments. (Adapted from http://www.scienzagiovane.unibo.it/english/radio-window/9_Instruments.html).

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Biographical Sketches

Luigina Feretti is *Dirigente di Ricerca* (Full Professor equivalent) at the Istituto di Radioastronomia (IRA) of Bologna, Italy, that is part of the National Institute of Astrophysics (INAF), and Director of the Institute since 2007. Her scientific activity is in the field of extragalactic radioastronomy, in particular non-thermal emission from galaxy clusters and cosmological magnetic fields. Dr. Feretti spent several periods working at the National Radio Astronomy Observatory in Socorro, New Mexico, USA, and at other scientific Institutions in Garching, Germany (Max-Planck Institut fur Extraterrestrische Physik) and in Saclay, France (Service d'Astrophysique CEA). She is the author of more than 280 papers published in scientific Journals and of several review papers. She has also edited scientific books. Dr. Feretti has been member of several International Committees and Panels, among them the Physics Evaluation Panel for Training and Mobility of the European Commission (1997-1998, FP4), the Physics Evaluation Panel of the Marie Curie Individual Fellowships of the European Commission (1999-2002, FP5). In the last panel she acted as Chairman both in 2001 and 2002. She is currently member of European VLBI Network (EVN) Board of Directors and vice-chairman the Joint Institute for VLBI in Europe (JIVE) Board. She is chairman since 2007 of the Board of the Sardinia Radio Telescope project. Dr. Feretti is one of the two Italian representatives on the Board of the Square Kilometer Array project. More information about Dr. Feretti can be found at her personal website http://www.ira.inaf.it/~lferetti/

Isabella M. Gioia is associated to the Institute of Radioastronomy (IRA) of Bologna, Italy, that is part of the National Institute of Astrophysics (INAF), where she was *Dirigente di Ricerca* until September 2011. Dr. Gioia works in extragalactic observational astronomy with particular interest in galaxy clusters. Her research is not confined to one wavelength but builds on observations in several domains from radio to optical and X-rays. Isabella M. Gioia spent several years working in the 1980s at the Harvard-Smithsonian Center for Astrophysics in Cambridge (USA) where, under the direction of Riccardo Giacconi, she was involved in several X-ray astronomy projects. She then moved to the Institute for Astronomy of the University of Hawaii (USA) where she could continue her research on extragalactic astronomy by accessing the biggest telescopes in the world located on the summit of Mauna Kea. She has published over 260 papers in Scientific International journals. Isabella Gioia is member of the International Astronomical Union for which she was the National Representative from 2006 to 2009, and the American Astronomical Society. Dr. Gioia served in the INAF Scientific Advisory Committee, from 2008 to 2011. She belongs to several committees and working groups and has acted as Principal Investigator for several research grants of *NASA* in USA, and *ASI* (Agenzia Spaziale Italiana) in Italy. She also acts as scientific referee for international astronomical journals. Isabella M. Gioia appears in the ISI List of World's Most Cited Physicists (http://hcr3.isiknowledge.com/). In 2005 Italy's President Ciampi honored her with "Grande Ufficiale dell' Ordine al Merito della Repubblica Italiana" for merit in the field of Scientific Research. The "Order of Merit of the Italian Republic" is the highest ranking honor of the Republic, and it is awarded for "merit acquired by the nation". More information about Dr. Gioia can be found at her personal website http://www.ira.inaf.it/~gioia/