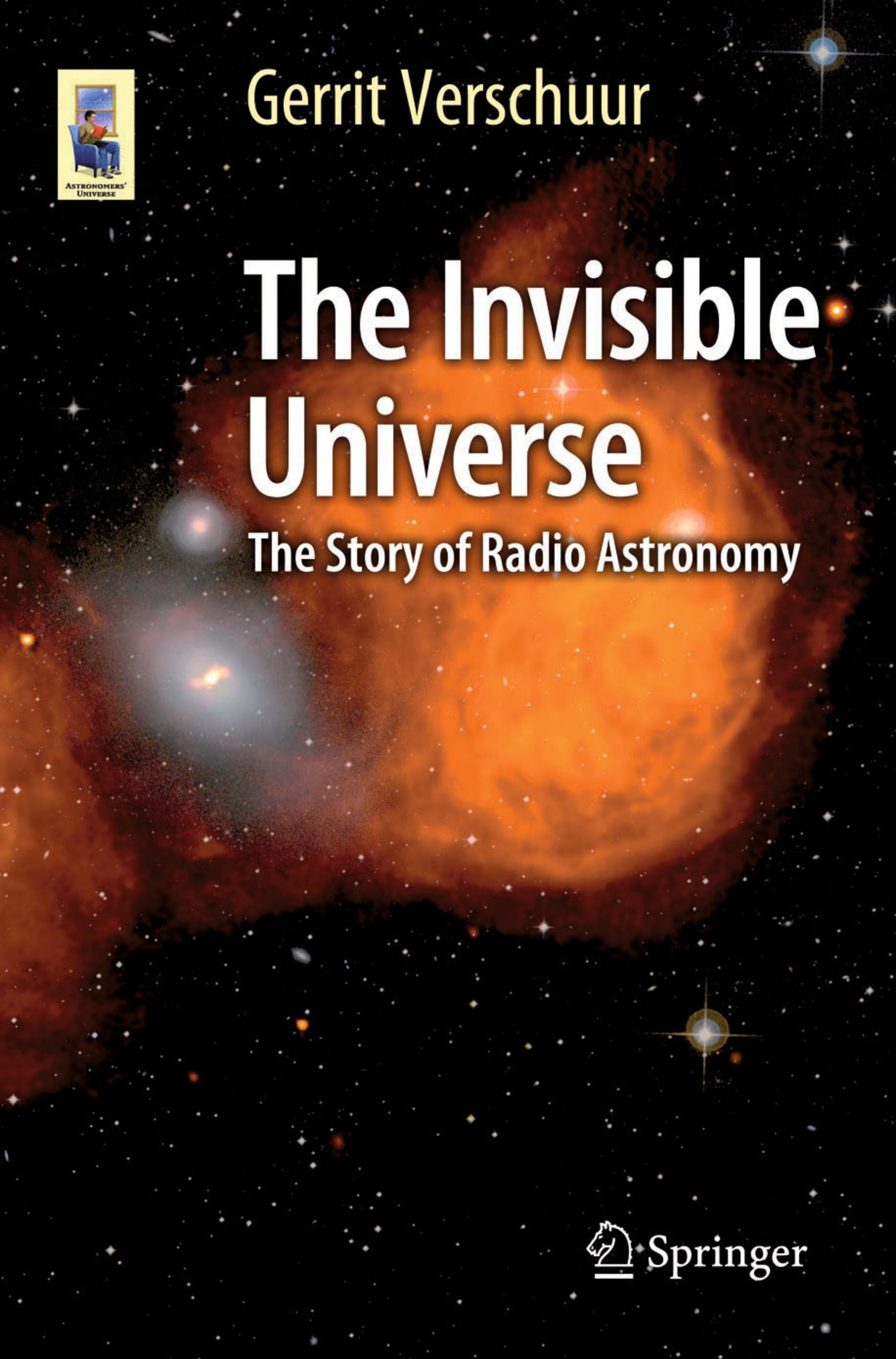
Gerrit Verschuur

# The Invisible Universe

## The Story of Radio Astronomy



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Gerrit Verschuur

# The Invisible Universe

## The Story of Radio Astronomy

Third Edition

Springer

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USA

Radiograph of the Fornax A radio source, centered on the giant elliptical galaxy, NGC1316 (center of the image), which is devouring its small northern neighbor. This Very Large Array image shows the radio emission to consist of two enormous radio lobes, each about 600,000 light-years across. The scale of such a structure is beyond human imagination, being a stunning six times the diameter of the Milky Way galaxy. Credit: NRAO/AUI/NSF. Investigators: Ed Fomalont (NRAO), Ron Ekers (ATNF), Wil van Breugel, and Kate Ebneter (UCBerkeley). Radio/Optical superposition by J. M. Uson.

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# Preface

This book is aimed at those who might have visited a radio observatory, a planetarium, a museum, or whose curiosity was otherwise stimulated by something they read in the papers or heard about on radio or saw on TV. It is also aimed at amateur astronomer as well as students of introductory courses in astronomy who wish to assuage their curiosity by reading more about the remarkable science of radio astronomy. In fact, if you are just curious, or wish to buy a book because your niece has expressed a youthful interest in science, this is for you.

## The Exploration of the Radio Astronomical Unknown

Radio astronomy is one of the great adventures of the human spirit. Exploratory behavior, the primal urge that drives us into the unknown, is rooted in curiosity and expressed in a deep human hunger for venturing into new worlds, a hunger that has been dramatically expressed in thousands of years of slow, systematic, and sometimes frightening journeys of exploration and discovery. Such journeys, overland and across the seas and oceans, have carried people from their birthplaces to the most distant corners of the planet and farther. Like pollen on the wind, our species has moved from the caves of earth to the craters of the moon. Our instinct drives us on, not just to the planets, but further, into the universe beyond our senses where profound mysteries have been uncovered, mysteries that challenge our imagination and our capacity for comprehension.

Radio waves from space carry information about some of the most intriguing natural phenomena yet discovered by human beings. This is the bailiwick of radio astronomy. However, the cosmic radio whispers reaching the earth compete with the electrical din produced by TV, radio, FM, radar, satellite, and cell phone signals. Thus the faint radio signals from space that memorialize the death of stars, or tell of awesome explosions triggered by black holes in galaxies well beyond sight, are nearly lost against the background of human-made static. Yet such radio waves contain the secrets of interstellar gas clouds, quasars and pulsars, and carry messages from the remnants of the Big Bang that propelled our universe into existence.

In order to gather the faint cosmic signals and avoid the unwanted stuff, astronomers use powerful radio telescopes located far from cities. Those telescopes are huge metal reflectors that focus the electromagnetic messages from space, which are then amplified in sensitive receivers and fed to computers where they are converted into a visual form to be displayed, analyzed, interpreted, and hopefully understood.

The story of radio astronomy is a tale of the constant quest to express in clearer visual forms the information carried by the radio waves. For this reason radio astronomers are always inventing new techniques to allow them to 'see' the radio sources more clearly. The better we 'see' the sources of those radio waves, the more likely we may be to understand their inner secrets.

Ever since Galileo first turned a telescope toward the heavens in 1609 AD, centuries of technological innovation have afforded an increasingly clear view of astronomical objects in the far reaches of space. Larger and more sophisticated telescopes are always being designed and constructed. Today, modern technological marvels such as the Hubble Space Telescope, the mightiest optical telescope ever built to date, allow astronomers to perceive the visible universe with fabulous clarity. Not to be outdone, giant radio telescopes, arrays consisting of dozens of individual dishes, now reveal the radio universe in even greater detail, and they have opened our imagination to a cosmos beyond our senses in ways previously undreamed of.

## Seeking New Knowledge

Like any science that seeks answers beyond the borders of the unknown, radio astronomy requires a great deal of thought and effort and, especially recently, significant amounts of money. In asking governments for funds to construct radio telescopes, the modern explorers of space are following a time-honored tradition. Voyages of discovery have always been costly affairs, usually sponsored by empires, monarchs, or business interests. Even Columbus needed a 'research grant' from Queen Isabella to carry him across the ocean. Today, tax dollars are used to fund expensive scientific instruments, which are the modern vessels of discovery, and the scientist/explorer's challenges have become far subtler than they once were.

In ancient times the sponsor of an explorer's journey had an expectation that the ship would return with a cargo of sugar, tobacco, spices, gold, or silver—something that could be used in barter. It is no longer so. The new explorer searches for knowledge—subtle, ethereal knowledge. This may be returned in the form of a radio image of a distant galaxy or of the invisible center of an interstellar gas cloud. It is impossible to attach financial worth to such images, just as it is impossible to attach value to any bits of that elusive substance called knowledge. What is clear, however, is that many of the pictures of radio sources in this book are beautiful in their own right even as they reveal the existence of previously unknown phenomena, knowledge of which broadens our perspectives about the universe into which we are born.

## This Third Edition

When the first version of this book was published in 1973 it was possible to summarize all of radio astronomical discoveries in a single monograph without overwhelming the reader. That was because the science of professional radio astronomy was barely 20 years old. Since then enormous advances in electronics and receiver technology has spurred a rapid growth in our ability to map the heavens in the radio band. A subsequent variation of this book, published in 1987, entitled The Invisible Universe Revealed, reflected the rapid growth of by including dramatic radio images, or radiographs, of distant sources of radio waves.

At the start of the twenty-first century our ability to produce stunning images of radio galaxies, for example, thanks to the impressive growth of computer technology, meant that the process of handling and displaying the data with color added for effect took another huge leap. (I do not subscribe to using the label 'quantum' to describe such a leap because a quantum is really a very, very tiny entity.) The official 2nd edition of The Invisible Universe published in 2007 included many of the most up-to-date colorized radiographs. In the nearly a decade since then the sheer volume of information that has been accumulated by a new generation of very large radio telescopes working over an increased wavelength range is staggering.

This 3rd edition of The Invisible Universe is timely because during the past decade radio astronomy has blossomed in dramatic ways. Previously I included a brief discussion of some planned radio telescopes, each a very large project, which have now come into being. The Atacama Large Millimeter Array (ALMA) is alive and well in Chile and significant segments of the Square Kilometer Array (SKA) operate in South Africa and Australia. What is fascinating about many of the new projects is their incredible isolation in scenically beautiful but stark locations. At the same time, China is coming into its own in the field of radio astronomy. It is within this context of progress that chapters have been updated, rewritten or added, and errors have been corrected.

# Acknowledgements

A book such as this cannot be produced without the input of a large number of colleagues, some in person, others through email. I am particularly grateful to the following for providing me with valuable information and/or help in tracking down the illustrations and apologize for any inadvertent omissions: Jim Moran, Peter Kalberla, Ken Kellermann, Alan Bridle, Meg Urry, Tom Dame, Mark Reid, Jim Braatz, Scott Ransom, Phil Diamond, Bernie Fanaroff, Justin Jonas, Rich Bradley, Tony Beasley, Di Li, Yihua Yan, Zhiqiang Shen, Flornes Yuen, Phil Diamond, Jacqueline Hewitt, Steven Tingay, Roy van der Werp, Katherine Blundell, Robert Kerr, Natasha Hurley-Walker, Christoph Malin, David Herne, William Garnier, Patricia Reich, Aaron Parsons, Sergio Martîn Ruiz, Nimesh A Patel, Peter Kalberla, W. Butler Burton, Lynley Merrington, Albert Zijlstra, and Nicolas Lira. I am also grateful for the continual help of my editor at Springer, Jennifer Satten.

The story of radio astronomy has of course been built on the work of many, many radio astronomers whose fundamental contributions cannot possibly be acknowledged in a finite space. But their work provided the mosaic of knowledge I have tried to convey in a coherent manner. The same is true of the many radio astronomy observatories in England, Japan, France, India, Italy, Germany, The Netherlands, Argentina, Australia, England and Canada not explicitly discussed but whose contributions continue to build the structure of our science. (Wikipedia gives a comprehensive list of over 100 radio telescopes, world-wide.)

Finally, I am profoundly grateful for the love and encouragement of my wife, Joan Schmelz in her support of many (sometimes unrelated) ventures in my life.

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# 1. What is Radio Astronomy

As you propel yourself into the invisible universe of radio astronomy, an explanation of some possibly unfamiliar terms will help guide you on your journey.

## 1.1 A Definition of Radio Astronomy

Radio astronomy involves the study of radio waves from the depths of space. Many objects in the universe emit radio waves through naturally occurring processes. Such objects include stars, galaxies, and nebulae, as well as a wide variety of peculiar, fascinating, and often mysterious objects, such as pulsars and quasars. Radio astronomers study such objects using a variety of radio telescopes, in their simplest incarnation metal dish-shaped reflectors, examples of which are scattered throughout this book. The famous one at Jodrell Bank in England is shown in Fig. 1.1, home base for your author for 7 years. Many of the astronomical objects that emit radio waves do not emit much or any light so that radio astronomers study what is essentially an invisible universe not seen by even the world's largest optical telescopes.

### How Radio Waves from Space are Generated

Cosmic radio waves are created in several ways, depending on the physical conditions in the radio-emitting object. Most of the processes involve the movement of electrons; in particular, changes in their velocity during which the electrons lose energy, which can be radiated away as a radio wave. Radio energy is produced either by slow-moving electrons (traveling between tens and hundreds of kilometers per second) within hot clouds of gas that surround very hot stars, for example, or by electrons that have been accelerated to near the speed of light through stellar or larger scale



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**Fig. 1.1** The 250 ft diameter radio telescope at Jodrell Bank in Cheshire, England. This image shows the upgraded version known as the Lovell telescope. At the *top* of the tall mast in the center of the dish electronic amplifiers attached to a small antenna (or feed, as it is called) are housed in the box at the focal point of the dish. The amplified signal is fed down to a laboratory at ground level or, in the days that I was using the dish, to our lab in the tower at the *right*. (Photo courtesy of Nuffield Radio Astronomy Laboratories, University of Manchester)

explosions, which energize the particles. The two radio emission processes are known, respectively, as thermal and non-thermal.

Non-thermal emission, sometimes called synchrotron radiation, involves cosmic ray electrons that spiral around magnetic fields and radiate energy and depending on the energy of the particle and the strength of the magnetic field, this process can produce emission at any of the wavelengths across the electromagnetic spectrum (see Appendix A.2). Other sources of radio waves from space involve the radiation from atoms or molecules, to be discussed in Chaps. 6 and 7.

## What is a Radio Source?

One of the earliest post-World War II discoveries in radio astronomy was that specific regions of the sky seemed to emit more radio energy than their surroundings. Those were given the generic name of 'radio source.' Whenever a larger radio telescope or more sensitive radio receiver was used, more radio sources were discovered. Today millions of radio sources are known.

The list of various types of radio sources includes stars, nebulae, galaxies, quasars, pulsars, the sun, the planets, as well as amazing clouds of molecules between the stars, all of which generate radio waves. The study of the cosmic radio waves—where they come from, how they are produced, what sorts of astronomical objects are involved—is what radio astronomy is all about.

## Single Dish Radio Telescopes

For hundreds of years, ever since Galileo who in 1609 AD first used an optical telescope to study the moon, stars, and planets, astronomers have used glass lenses or a mirror to gather and concentrate light from distant stars and galaxies. The light is then passed through more lenses to bring it to focus on a photographic plate or on a detector to be converted into electrical signals.

In its simplest form a dish-type radio telescope is similar to an optical telescope, but it reflects radio waves off a metal surface instead of a glass mirror. The larger the reflecting surface the greater the amount of energy gathered and the fainter the radio signals that can be sensed.

In January 1961 I arrived at Jodrell Bank to begin my postgraduate work, having just arrived from South Africa. It was a foggy day and I could not see the giant telescope until I was nearly under it. When it loomed out of the fog I was overwhelmed by its awesome size. That image remains deeply etched in my memory. The laboratory of the group I had joined was located 120-ft above ground in what was called the Green Tower, on the right in Fig. 1.1. The walls of this lab were made of steel plates and had no insulation. The important elements of the receiving system were in a small, heated enclosure in the lab that barely allowed us to enter to make adjustments when needed. During the infamous winter of 1962–1963 in England the temperature inside this lab dipped below freezing and remained there for weeks despite having heaters going to keep us warm. After tedious trips up to the focus located 60 feet above the dish (at the time), which required a 4 min one-way ride in a small funicular platform, any attempts to warm my feet by an electric fire upon my return to the lab tended to set my socks smoldering before I even knew that the heat was on. Our midnight observing runs, which required remaining awake from midnight until 10 a.m. tending to paper chart recorders and fixing anything that had failed were a test of endurance. They were also dramatic and fun.

Radio waves from space are reflected off the parabolic surface of the dish to a focus where a small antenna, usually called a 'feed' collects the signals. The feed may be a simple dipole but most often it is a horn antenna designed to soak in as much of the received radio energy as possible. The concentrated radio signals are then converted into electrical voltages in amplifiers connected to the horn. This is known as the 'front end' of the receiver. Those voltages are then sent to the control room where they are amplified a million or more times in the 'back end' of the receiver before being processed in a computer to be displayed in such a way that the radio astronomer can 'see' what the data indicate.

A single-dish radio telescope (see also Appendix A.1) will collect all the radio energy coming from some small area in the heavens at any instant. That area is called the beam and defines the resolution of the telescope, which depends on the observing frequency and the diameter of the dish. The larger the diameter or the higher the frequency, the better the resolution (smaller beam width). The 250 ft radio telescope shown in Fig. 1.1 has a beam width of about 12 arc min at a frequency of 1420 MHz.

In order to produce the equivalent of a photograph the single-dish radio telescope has to be systematically "scanned" across of a section of sky in the same way that a TV image is produced by scanning an electron beam across the TV screen. The intensity of received radio signals is recorded and the data combined to produce a radiograph, the visual image of what a particular direction in the sky looks like to the radio telescope.

## 1.2 Radio Interferometers

The accuracy with which the first radio sources were located in the sky was insufficient to allow optical astronomers to decide which of the hundreds or thousands of images of stars, galaxies, and nebulae in their photographs of the region in question was responsible for the radio emission. In order to make an optical identification the astronomers required an accuracy of 1 arc min or less (Appendix A.6), although by the late 1940s and early 1950s half a dozen of the strongest radio sources had been identified with obviously unusual, and hence interesting, optical objects. Those included a couple of nebulae associated with the remains of exploded stars, and several distant galaxies.

In order to 'see' more clearly the radio astronomer needs, above all, high resolution. While the larger the diameter of a single dish antenna the better its resolution, there is a limit to how large a structure can be built before it collapses under its own weight. Instead, in the quest for higher resolution, radio astronomers began to combine the signals from two dishes separated by miles in what is called an interferometer whose resolution is determined by the distance between the component dishes.

A very beautiful variation of a simple interferometer was developed at Cambridge by radio astronomers led by Sir Martin Ryle. In this technique, the aperture (or area) of a very large dish is synthesized using many small dishes located far apart, and their individual signals are sent to a powerful central computer.

Aperture synthesis, as it is called, works as follows: Imagine two 10 m diameter dishes located on a football field and pointed at a given radio source. If you store the radio signals from each of these dishes as they are moved to every point on the field and then combine all the data, it is possible to synthesize what you would have observed had you used a single dish of the size of the entire football field. What Ryle and his team realized was that, as seen from the radio source, any two radio telescopes appear to move around each other during the day due to the rotation of the earth. That means you don't have to physically move the dishes. You just let the earth do the walking. Enormous apertures can be synthesized in this way.

In practice, aperture synthesis involves using an array of many dishes spread over dozens of miles of countryside.

**Fig. 1.2** The VLA radio telescope of the National Radio Astronomy Observatory located west of Socorro, NM, out in the middle of nowhere, which is what radio astronomers prefer in order to avoid unwanted radio interference. In this view the dishes are spaced in the so-called compact array. The railroad tracks on which the dishes can be moved for up to 11 miles along each of three arms of the array can be seen in the foreground. The VLA uses the principles of aperture synthesis to create images of radio sources and now is part of the even larger Expanded VLA, also known as the Jansky VLA. (Credit NRAO/AUI/NSF)

## The Very Large Array

The world's largest aperture synthesis telescope is the Expanded Very Large Array (EVLA), centered 50 miles west of Socorro, in New Mexico, is one of the National Radio Astronomy Observatory's (NRAO) repertoire of beautiful radio telescopes (Fig. 1.3). Observations with the VLA were used to make many of the radiographs shown in this book. Twenty-seven individual radio antennas of 25 m diameter are located along railroad tracks, which are laid out in a Y-shape, each arm of which is 23 km long. To completely synthesize the largest possible aperture obtainable by the VLA the individual antennas have to be moved to different locations along the rail tracks every few months (Fig. 1.2).

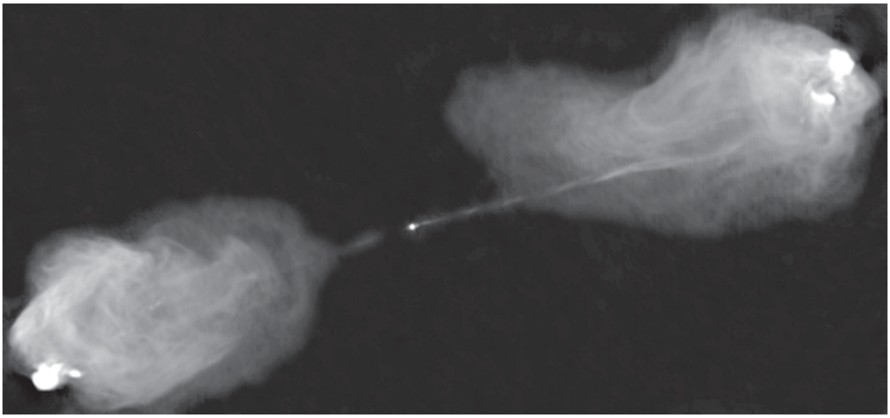

**Fig. 1.3** A radio image, or radiograph, of Cygnus A, one of the most powerful sources of radio waves in the heavens, as observed with the VLA. Tenuous filaments of radio emitting gas constrained by magnetic fields illuminate two enormous lobes fed by jets blasted 100,000 light years out into space on either side of a central galaxy located 600 million light years from earth (see Chap. 10). (Credit: NRAO/AUI/NSF. Investigators: R. Perley, C. Carilli, and J. Dreher)

One of the most stunning images ever made using data from the original version of the VLA is of a radio source known as Cygnus A, shown in Fig. 1.3.

The expanded VLA has doubled the size of the VLA in terms of the maximum baselines that can be attained using a number of outlying radio dishes.

## Very Long Baseline Array

The Very Long Baseline Array (VLBA) is a continent-sized radio telescope (Fig. 1.4) capable of enormously high resolution. Ten antennas are located from St. Croix in the Virgin Islands to Hawaii, with eight distributed over the continental United States. As with all new antenna arrays, the resulting radio telescope operates on aperture synthesis principles. The VLBA can attain an angular resolution of two tenths of one thousandth of an arc second (0.2 million arc s), which may be compared with 1 arc second for the typical radiographs shown in this book.

**Fig. 1.4** The location of the 10 dishes that make up the VLBA radio telescope of the NRAO. Data from all the out stations are brought together at the central processing computer in Socorro, NM. All combinations of baselines connecting the individual dishes at the various sites (shown as *red lines*) are used to construct a simulated singe dish radio telescope of this total size. (Credit: NRAO/AUI/NSF)

### The Current Epitome of Array Telescopes (ALMA)

Now coming into full operation is the Atacama Large Millimeter Array (ALMA) in Chile, which produces unprecedented clear images of radio sources at millimeter wavelengths. Figure 1.5 is a beautiful photo of the inner group of telescopes, part of the 66-dish array, photographed at the moment that a bright fireball entered the earth's atmosphere. Christoph Malin produced this image; see his fabulous web site showing a time-lapse sequence of the ALMA telescopes moving throughout a night.

It will be my policy in the chapters to follow to draw the reader's attention to web sites that communicate more about specific topics, and in this case it is http://vimeo.com/channels/christophmalinshortfilms. More about ALMA is to be found in Chap. 14.

## 1.3 And Now for Something Practical

Cautious readers may wonder if radio astronomical research has a practical or useful side in addition to adding to the font of humanity's knowledge about the invisible universe. The immediately

**Fig. 1.5** A photo of a cluster of radio dishes that make up ALMA taken just as a fireball, a very bright shooting star, slashed across the sky. (Credit: ESO.org/Christoph Malin)

practical comes from a rather fascinating use of the VLBA mode of operation.

An example can be found in the use of a telescope network set up by European radio astronomers. They have linked up more than a dozen dish-type telescopes in what is called the European VLB Network with individual dishes located as far south as South Africa, as far East as China, and as far north as Spitsbergen, an island north-east of Greenland in the archipelago known as Svalbard, a Norwegian territory. Figure 1.6 shows the 20 m (65 ft) diameter dish located about 2 km from the tiny village of Ny Ålesund, the most northerly, permanently inhabited place in the world. Year round about 35 people inhabit the village and in the summer the number swells to more than 120 as scientists converge to carry out polar-related research.

The primary role of the Ny Ålesund radio telescope as part of the European VLB Network is, strictly speaking, as a geodetic observatory. That means it is used to measure earth movements. Every day the telescopes of the Network observe distant quasars and in order to make sense of the data the scientists need to know

**Fig. 1.6** A 78° 55′ North latitude the radio telescope in Ny Ålesund in the Spitsbergen islands, also known as Svalbard, forms part of the European VLB Network and is used mainly for geodesy. Regular observation of quasars allows the annual shift in location of the island to be determined. In the background a glacier seems to threaten its existence. (Photo by the author taken from a cruise ship in King's fiord)

precisely where the various radio telescopes are located. Therefore, by observing quasars (see Chap. 11) year after year they can calculate the movement of the various radio dishes in the network with respect to one another. As a result of years of monitoring they know that the Ny Ålesund radio telescope is moving north at 14.3 mm per year, east at 9.8 mm/year, and vertically at 8.2 mm/year. Much of the movement is attributed to post-glacial rebound since the last ice age. In the same way, such radio telescope based arrays can measure continental drift and in the case of a network in the USA, motions along the two sides of the San Andreas fault in California.

## 1.4 How Far Can Radio Telescopes 'See'?

Whenever someone hears that I am a radio astronomer, and after they have passed through the confusing phase of thinking this is some form of astrology, I am often asked, "How far can the radio telescope see things?" Bearing in mind that radio telescopes are not something you can see through, we nevertheless use the colloquialism of 'seeing' radio waves. That is part of the jargon of the trade. We can't say we listen to radio signals from space either, because there is nothing to hear that the human ear can detect against the background 'noise' produced by the radio receivers attached to the radio telescope. (It is a sign of the times that a single-dish radio telescope is best described as a large satellite dish!) Instead, we look at the output of a computer program that converts the radio signals generated by a host of interesting physical events in the depths of space into numbers or maps of what those objects would look like if you could literally "see" radio signals.

As regards the question "How far can a radio telescope see?" I usually respond that they can see farther than the Hubble Space Telescope, very nearly to the beginning of the universe. The reason is simple. Virtually every radio telescope ever constructed, if equipped with a suitably sensitive receiver, could, in principle, detect the faintest of whispers left over from the Big Bang (Chap. 13), provided reception is not swamped by terrestrial signals (interference) that all too readily overwhelm any signals reaching those dishes from outer space.

# 2. A Science is Born

## 2.1 A Touch of History

In 1886, Heinrich Hertz accidentally constructed the first radio transmitter and receiver. In a darkened lecture theater at the Technical College in Karlsruhe, in Germany, Hertz had set up an experiment to test what happened when an electrical current flowed in an open circuit (that is, a circuit with a gap in it). As he explained the setup to his wife, Elisabeth, he switched on a spark generator, used to produce current, and one of them noticed a simultaneous spark that flashed in an unrelated piece of equipment at some distance away from his main experimental apparatus. Whoever noticed it first, Heinrich or Elisabeth, is unknown to us, but it was Heinrich who made the leap of curiosity that underscores the nature of scientific research. Hertz asked "Why?" and started a systematic search for an answer.

Eighty years later historians of science would report that Hertz was at least the sixth physicist to see this odd effect, but he was the first to follow up on his key question. He proceeded to design a series of brilliantly simple experiments, one after another, in search of an answer. He was able to show that an invisible form of radiation, which he called 'electric waves,' carried energy through intervening space. Hertz was also able to demonstrate that the electric waves were a phenomenon very similar to light. In fact the speed of those waves through the air was the same as that of light. Today we know that both light and Hertz's electric waves are forms of electromagnetic radiation (see Appendix A.3). Over time, the Hertzian waves (a name used very early in the twentieth century) came to be called radio waves. Their frequency is measured in cycles per second, now called Hertz (Hz). In Appendix 3.1 the relationship between frequency and wavelength is explained. For the bulk of our story we will refer to the frequency of radio waves.


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Hertz died tragically at the young age of 35 of blood poisoning from an infected tooth. If he hadn't, he surely would have won a Nobel Prize in Physics for his discovery.

After showing that radio waves behave much as light does, except that they are utterly invisible, Hertz did not ask how far they might travel through space. That was left to Guglielmo Marconi, the Italian physicist who performed a series of obsessively creative experiments to prove that radio waves could travel enormous distances and even pass through rock. He was wrong in this latter belief, but he did show that radio signals could traverse the Atlantic Ocean. The reason that the radio waves made it across despite the curvature of the earth was because the earth's atmosphere is surrounded by an electrically conductive layer known as the ionosphere and radio waves bounce off that layer to be reflected across the ocean. That wouldn't be understood until decades later. Meanwhile, Marconi was happy to know that radio waves did go all the way around the earth and it was not long before ships at sea could signal one another across the ocean using radio waves. In 1912 the infamous sinking of the Titanic spread awareness that radio transmitters could be used to send an SOS far and wide.

Marconi did wonder whether there might be radio waves reaching earth from space but his equipment would not reveal the existence of the wondrous invisible universe for the same reason that he could signal across the Atlantic. At the low radio frequencies that Marconi used, the reflecting ionosphere not only allows radio signals to bounce around the curvature of the earth, it also prevents radio waves from space from penetrating to the earth's surface. Those that do arrive from space are absorbed or reflected back. (Only if their intrinsic frequency is higher than about 20 MHz do such radio waves reach the ground unimpeded, but back then not much was known about building receivers at such frequencies.)

## 2.2 The Birth of Radio Astronomy

Karl Guthe Jansky, the father of radio astronomy, was employed at Bell Laboratories, which, in 1927, introduced the first transatlantic radiotelephone. For a mere $ 75 one could speak for three minutes between New York and London, but the radio links were

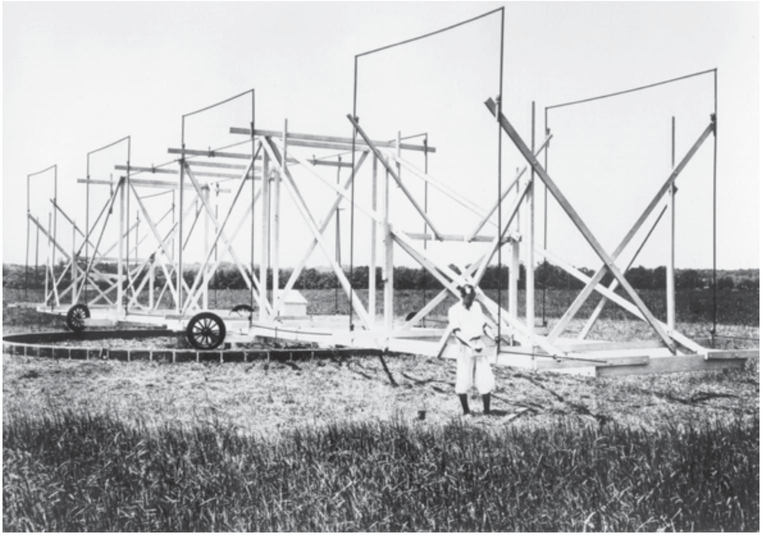

**Fig. 2.1** Karl Jansky, working at Bell Telephone Laboratories in Holmdel, NJ, in 1928 built this antenna to receive radio waves at a frequency of 20.5 MHz (wavelength about 14.5 m). It was mounted on a turntable that allowed it to be rotated to be oriented in any direction, earning it the name "Jansky's merry-go-round." He duly discovered the direction from which the mysterious hissing radio signals were arriving, the Milky Way, in particular its center in Sagittarius. (Credit: NRAO/AUI/NSF)

terribly susceptible to electrical interference. The first system operated at the extraordinarily low frequency of 60 kHz (that is, at the very long wavelength of 5 km) and in 1929 a change was made to frequencies in the range 10–20 MHz. But the new telephone links were still susceptible to electrical disturbances of unknown nature, which plagued the connections. Jansky was assigned the task of locating the source of the interference. To carry out his studies he built a rotating antenna (Fig. 2.1) operating at 20.5 MHz and by 1930 began making regular observations. In 1932 he reported that local and distant thunderstorms were two sources of radio noise and a third source was "a very steady hiss-type static, the origin of which is not yet known."

During the following year he demonstrated that the source of the signals was outside the earth and presented a report entitled "electrical disturbances apparently of extraterrestrial origin." And so radio astronomy was born.

Just imagine this: When Jansky became convinced he had picked up radio waves from space he enjoyed what few people ever experience—the thrill of discovery—finding something no one had ever known about before. That is part of the reward, the joy, and the excitement of doing scientific research.

Fifty years later, at the National Radio Astronomy Observatory in Green Bank, West Virginia, distinguished radio astronomers gathered to celebrate the anniversary of Jansky's discovery. A report entitled "Serendipitous discoveries in radio astronomy"[1] grew out of that meeting and it presents the human side of the birth and growth of this science.

"Serendipity" is a term coined by Horace Walpole, the writer and historian, who used it to refer to the experience of making fortunate and unexpected discoveries, according to the fairy tale about the three princes of Serendip (an old name for Ceylon). Serendipitous discoveries are those made by accident, but also by wisdom; however, no one will make an accidental discovery unless that person is capable of recognizing that something of significance is occurring. Jansky was such a person.

In January 1934, in a letter to his father, Jansky wrote:

> Have I told you that I now have what I think is definite proof that the waves come from the Milky Way? However, I'm not working on the interstellar waves anymore.

His boss had set him to work on matters of more immediate concern, matters, which were:

> … not near as interesting as interstellar waves, nor will it bring near as much publicity. I'm going to do a little theoretical research of my own at home on the interstellar waves, however.

Jansky did not take an interest in his new discoveries to the point of building his own antenna so as to pursue his explorations over the weekends. Jansky's boss, who ruled with an iron hand, was later to encourage him to write another report, and in 1935 Jansky interpreted the sky waves as coming from the entire Milky Way. But he did not know why and suggested that either a lot of stars were contributing or perhaps something in interstellar space was the cause. He realized that if the waves were due to stars he should have detected the sun. As observed from the surface of the earth

[1] K. Kellermann and B. Sheets (eds.), *Serendipitous Discovery in Radio Astronomy*, National Radio Astronomy Observatory, Green Bank, WV, 1983.