The Invisible Universe
SECOND EDITION

Gerrit Verschuur

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The Story of Radio Astronomy

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Springer

Gerrit Verschuur
University of Memphis
Memphis, TN 38002

Library of Congress Control Number: 2006924881

ISBN-10: 0-387-30816-4 Printed on acid-free paper
ISBN-13: 978-0387-30816-6

Printed on acid-free paper.

9 8 7 6 5 4 3 2 1

springer.com

Dedicated to the memory of Heinrich and Elisabeth Hertz who lit the spark that illuminated the invisible universe.

Acknowledgments

When the first version of this book was published back in 1973 it was possible to summarize all of radio astronomical discoveries in fair detail in a single monograph without overwhelming the reader. That was because the science of radio astronomy was barely 20 years old since technology had spurred a rapid growth in our ability to map the heavens in the radio band. The subsequent edition of this book, published in 1987, entitled The Invisible Universe Revealed, reflected the rapid growth of this science by including dramatic radio images, or radiographs, of distant sources of radio waves.

At the start of the 21st century our ability to produce stunning images of radio galaxies, for example, is a matter of routine and color is readily added for effect. In this edition we have included several of the most informative colorized radiographs made to date. Another enormous change seen over the last 20 years is the sheer volume of information that has been accumulated by a generation of very large radio telescopes working over an increased wavelength range. Therefore it is no longer possible to provide a comprehensive overview such as the one that made up the 1973 edition.

It is with this caution in mind that we enter the Invisible Universe of radio astronomy to describe its contents in broad terms, cognizant that to go into more detail would make this book unacceptably long (and expensive!). Also, in producing this new edition I have kept in mind the interests and potential needs of the intelligent lay person who might have visited a radio observatory and who then seeks to assuage their curiosity by reading more about this science.

The present rewrite would have been impossible without the input of a large number of colleagues, some in person, others through email, and the help of staff at the National Radio Astronomy Observatory. Also, each of the images shown in this book required a large amount of careful work on the part of dozens upon dozens of colleagues who together have turned the invisible universe of radio astronomy into a gallery of visual representations that stagger the imagination. Thus it is with great pleasure that I list those who have helped in re-educating me, and those who provided information that made my task possible. I apologize for any inadvertent omissions.

Thank you Sue-Ann Heatherly, for encouraging me to take on the project, and my wife Joan Schmelz for seconding the motion and for her subsequent urging and encouragement as well as her editorial advice, to Barry Turner for having been a great office mate for years in the youthful days of radio astronomy, and for helping establish a reliable molecule list, with assistance from Al Wooten, and Butler Burton for his overall enthusiasm for the project and help in getting it started.

This revision would not have been possible without the help of the following colleagues: Fred Lo, Miller Goss, Patricia Reich, Rainer Beck, Cornelia Lang, John Hibbard, Dave Hogg, Scott Ransom, Jim Moran, Mark Reid, Harvey Lizst, Peter Kalberla, Ed Fomalont, Ken Kellermann, Alan Bridle, Katherine Blundell, Meg Urry, Juan Uson, Alan Bridle, Elly Berkhuijzen, Dave Jauncey, Charles Lada, Tom Dame, Jim Braatz, Steve Schneider, Baerbel Koribalski, Lister Staveley-Smith, Paul Vanden Bout and to NRAO staff members Billie Rodriguez, Pat Smiley, and Marsha Bishop.

Thank you one and all, and enjoy.

Contents

Introduction: Adventure, Imagination, and Curiosity

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 evolution. 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 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, allow astronomers to perceive the visible universe with fabulous clarity. Not to be outdone, giant radio telescopes reveal the radio universe in comparable detail, and they have opened our imagination to a cosmos beyond our senses in a way 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 a new radio telescope, the modern explorers of space are following a time-honored tradition. Voyages of discovery have always been costly affairs, usually sponsored by monarchs, business interests, or empires. Even Columbus needed a "research grant" from Queen Isabella to carry him across the ocean. Today, tax dollars fund scientific instruments, the new vessels of discovery, and the scientist/explorer's challenge has become far more subtle than it once was.

In ancient times the sponsor of an explorer's journey had an expectation that the ship would return with a cargo of 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.

Radio Astronomy and Imagination

The invisible universe of radio astronomy is revealed in images that startle the imagination. Although this book contains only static pictures, each radiograph is a snapshot of an object in a state of continual upheaval. The motion, the chaos, and the violence found in the invisible universe can only be recognized when you wrap your imagination around the images. Do not hesitate, because your imagination is as valid as the next person's in trying to visualize this.

Full appreciation of the new discoveries requires the continual involvement of your imagination. Exploration of the cosmos becomes an adventure when it takes place in the mind. The explosion of a quasar is not witnessed in space somewhere, but in your imagination. All we see out there, now, is but an instantaneous snapshot of what took place millions or even billions of years ago.

The dynamical aspects of astronomy are revealed not by what is seen at the far end of the telescope, but what is experienced at this end. This is where the excitement is to be found. Thanks to the workings of the human mind, aided by physics, mathematics, and computers, astronomers can simulate cosmic phenomena that allow us to recognize how evolution, change, and catastrophic events shape distant gas clouds, dying stars, galaxies, and quasars.

The human race looks out into space and discovers marvelous beauty, a beauty that often lies beyond our normal powers of perception. Yet it is a beauty that can touch us as profoundly as any terrestrial sunset, symphony, or songbird. In radio astronomy the beauty is perceived by fully harnessing our imagination as we travel beyond the senses. In the following pages you will join in the adventure and share the excitement of exploration as we journey into the invisible universe, a universe revealed by tiny amounts of radio energy reaching us from millions or even billions of light-years away.

1
What is Radio Astronomy?

1.1. A Little 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 curiosities that underscore 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 their speed 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.2). Over time, the Hertzian waves (a name used very early in the 20th century) came to be called radio waves. Their frequency is measured in cycles per second, now called Hertz (Hz). In Appendix 2.1 the relationship between frequency and wavelength is discussed. For the bulk of our story we will refer to the frequency of radio waves.

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 a radio signal 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 that ships at sea could signal one another and to their home ports using radio waves. By 1912 the infamous sinking of the Titanic spread awareness that radio transmitters could 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 reaching the earth's surface. Those that do arrive from space are reflected back. (Only if their intrinsic frequency is higher than about 20 MHz such radio waves do reach the ground unimpeded, but then it was not known very much about building receivers at such frequencies.)

1.2. 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 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 short waves whose frequencies were in the range of 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 (Figure 1.1) operating at 20.5 MHz and by 1930 began taking regular observations. In 1932 he reported that local and distant thunderstorms were two sources of the 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 was unambiguously able to demonstrate 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—seeing something no one had ever seen before. That is part of the reward, the joy, and excitement of doing scientific research.

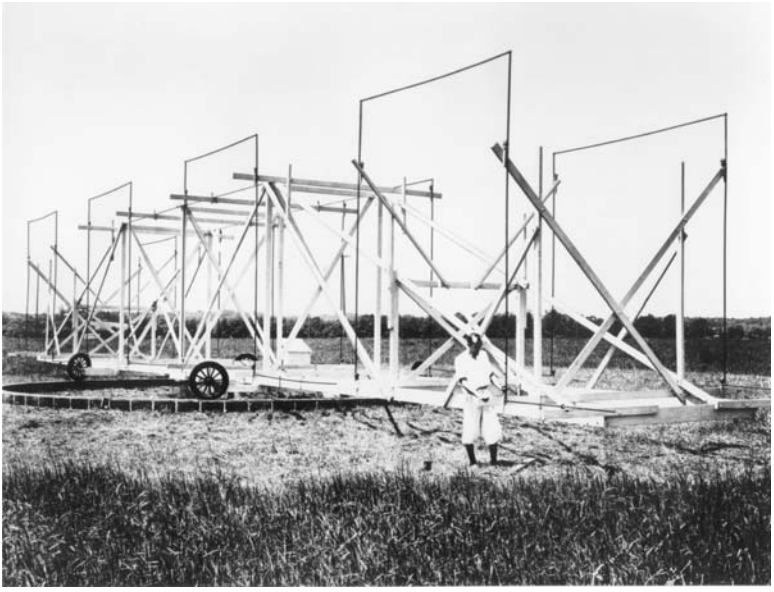

FIGURE 1.1. Karl Jansky, working at Bell Telephone Laboratories in Holmdel, NJ, in 1928 built this antenna to receive radio waves at a frequency of 20.5 MHz (wavelength about 14.5 meters). It was mounted on a turntable that allowed it to rotate in any direction, earning it the name "Jansky's merry-go-round." By rotating the antenna, he could find what the direction from which radio signals were arriving. In this way he identified radio waves coming from the Milky Way, in particular its center inn Sagittarius. (Image courtesy of NRAO/AUI.)

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" 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 can 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: