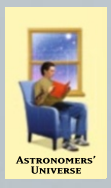

R. H. Frater · W. M. Goss
H. W. Wendt

Four Pillars of Radio Astronomy: Mills, Christiansen, Wild, Bracewell

Springer

Astronomers' Universe

Series editor
Martin Beech, Campion College, The University of Regina, Regina, Saskatchewan, Canada

More information about this series at http://www.springer.com/series/6960

R.H. Frater • W.M. Goss • H.W. Wendt

Four Pillars of Radio Astronomy: Mills, Christiansen, Wild, Bracewell

Springer

R.H. Frater
Lindfield, NSW
Australia

W.M. Goss
National Radio Astronomy Observatory
Socorro, New Mexico
USA

H.W. Wendt
Vaucluse, NSW
Australia

ISSN 1614-659X ISSN 2197-6651 (electronic)
Astronomers' Universe
ISBN 978-3-319-65598-7 ISBN 978-3-319-65599-4 (eBook)
DOI 10.1007/978-3-319-65599-4

Library of Congress Control Number: 2017952246

Cover image: Four piers (or pillars) in the Bracewell Radio Sundial at the Karl G. Jansky Very Large Array in New Mexico, USA. Photo courtesy of W.M. Goss. 1 April 2017. For more information, see page xv

Cover credit: by R.H. Frater, W.M. Goss, H.W. Wendt

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Bob Frater: To my wife, Margaret

Miller Goss: For Martin Y. Smith – who made my research on the history of Australian radio astronomy possible

Harry Wendt: For Susan and Tom

Foreword

As one of the beneficiaries of the contributions of these four scientists, it is a privilege to provide the foreword to this book. As a student at the University of Adelaide in the early 1960s, I attended a lecture by Bernie Mills, my introduction to radio astronomy. Later, as a summer student at CSIRO, I learned about radio telescope arrays from Chris Christiansen. *Radiotelescopes* by Christiansen and Högbom and *The Fourier Transform and Its Applications* by Bracewell strongly influenced my career. I visited Ron Bracewell at Stanford in 1968 and added my signature to the telescope pier now illustrated on the front cover of this book. The Australia Telescope Compact Array (ATCA) grew from the tradition of innovative radio astronomy instrumentation discussed in this book. I became its first director. The proposal to make ATCA part of a National Facility was led by Paul Wild, while chairman of CSIRO. One of the authors, Bob Frater, recruited me from the National Radio Astronomy Observatory in the USA as part of a team to develop and operate this new facility.

The authors felt the influences as well. Miller Goss is the world expert on Joe Pawsey and his role in the history of radio astronomy in Australia as mentor to the *Four Pillars*. Bob Frater took up the mantle of the *Pillars* by rejuvenating Australian Radio Astronomy in the 1980s. Harry Wendt is a professional historian who wrote his thesis on the instruments built by the *Four Pillars* and their observatory sites.

This book is not just a collection of stories about four very successful radio astronomers but of the connections between these scientists and a culture which resulted in a profound global influence in the field of imaging radio astronomy. By pulling the careers of these four scientists together, the authors have given us a wonderful cross section of the development of radio astronomy as an exciting new research area. It was a remarkable period in the history of Australian science, when radar research at the end of World War II resulted in an unusual concentration of scientific talent in this isolated country. This was a crucial period in the history of Australia radio astronomy when the competition for resources caused the radio astronomy community, initially concentrated in CSIRO, to split. The *Four Pillars*

each went in different directions: Bracewell to Stanford in California, Mills to the University of Sydney physics and Christiansen to University of Sydney engineering; only Wild stayed at CSIRO, eventually becoming the chairman of the organisation.

Each of the *Four Pillars* was involved in the invention of new instruments and algorithms to further the development of imaging in radio astronomy. Mills invented the Mills Cross, Christiansen the Chris Cross and Wild the solar heliograph, and Bracewell provided the mathematical basis for indirect imaging. This snapshot in the development of radio astronomy imaging illustrates the complex interplay between the design of antenna arrays and the formation of images. They each took a different path to solve this problem. Chris made the first earth rotation aperture synthesis image, but to do so he had to use laborious hand calculations of the Fourier transforms. Mills used analogue beam formation with an ingenious array design – the famous "Mills Cross". This avoided the need to calculate Fourier transforms but, in time, it was the digital computers that dominated the field. Mills eventually modified his cross to take advantage of this new technology. Wild successfully played the middle ground and cleverly exploited analogue computers to generate time-varying two-dimensional images of the radio sun – a feat which was only matched by modern aperture synthesis methods in the last decade. Bracewell made a career from the development of mathematical models and algorithms and played a key role in the introduction of Fourier methods based on radio astronomy imaging to the medical imaging field. To quote Bracewell from the end of Chap. 7: "Starting from modest beginnings and by small steps, radio astronomers took the separate field of antennas, receivers and information theory and welded them into image forming systems that have improved by seven orders of magnitude in resolution, surpassing the optical telescope, and inspired other developments in fields as diverse as optics, acoustics, seismic probing and X-ray tomography".

The science the *Four Pillars* covered is remarkably diverse. Mills was involved in both galactic and extragalactic astronomy and in cosmology. Paul Wild made the definitive observations of solar radio activity as well as contributions to ionospheric research, the theory of the atomic transitions of hydrogen and the measurement of magnetic fields in the interstellar medium. Christiansen confirmed the predicted brightening of the limb of the sun. Bracewell's key contributions were the mathematical principles involved in indirect imaging and hence in image deconvolution theory.

The story of Wi-Fi and 802.11 is covered in detail in Chap. 7. The complex history of this development is a key part of this book and illustrates the many complicating factors involved in the creation of a new technology. Many of Chris's students played key roles in the 802.11 wireless development including O'Sullivan, Daniels, Percival and Skellern. One author, Bob Frater, also played a part, and he has contributed to this unique in-depth analysis of how it happened.

The *Four Pillars* started an unbroken line of instrumental developments in which Australia has continued to play a global role. They sowed the seeds that have now led to Australia's involvement in the Square Kilometre Array (SKA) – a

major astronomical project with the Murchison Widefield Array (MWA) and the Australian Square Kilometre Array Pathfinder (ASKAP) as its precursors. The authors also speculate, however, on whether the current research and funding environments will still allow new ideas to blossom and whether we are still identifying and mentoring the next generation of systems thinkers needed to implement the new ideas.

R.D. Ekers

Preface

As authors of memoirs of Bernard Mills (Frater, Goss, & Wendt, 2013), Chris Christiansen (Frater & Goss, 2011), Paul Wild (Frater & Ekers, 2012) and Ron Bracewell (Thompson & Frater, 2010), we could not avoid the realisation of their profound effect on the development of (imaging) radio astronomy on a global scale and the fact that they were a unique group of pioneers whose stories should be brought together (see Fig. 1).

Bob Frater and Miller Goss had first-hand interactions with the *Four Pillars* during the early 1960s until their deaths. Bob Frater, as an author on all four of the memoirs, saw the incredible influence these men, his mentors, had had on his life and career. They, in turn, were greatly influenced by a remarkable individual who had been their scientific leader and mentor in their early careers – Joseph Lade Pawsey.

The contributions of each of the *Four Pillars* to the development of radio astronomy were significant in their own right. Mills is remembered for the invention of the cross-type radio telescope that now bears his name and for his contribution to the understanding of the nature of discrete radio sources. He is also remembered for his prolonged battle with one of the giants of radio astronomy, Martin Ryle of Cambridge, over the validity of the radio survey source count data that Ryle was using to base conclusions over which cosmologic model was correct: either the "Big Bang" or "Steady State" model. This was a period when astronomers and theorists were just awakening to the potential of radio astronomy to shed new light on the nature of the universe. Christiansen is remembered for his invention and designs of array-type telescopes and for his application of earth rotational synthesis to produce high-resolution images. His influence, both direct and indirect, extended to the design of radio telescopes throughout the world. Wild is remembered for his masterful joining of radio observations and theory to elicit the nature of the solar atmosphere. His invention of the major classification types of solar radio bursts has stood the test of time and is still in use today as the standard classification. Wild's work dominated the field of solar radio astronomy for over three decades.

Fig. 1 The authors (L-R) Miller Goss, Harry Wendt and Bob Frater sitting down to plan the Four Pillars in July 2014 at the CSIRO offices in Lindfield, Sydney

He is also remembered for his leadership of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) later in his career. Finally, Bracewell is remembered for his contribution to the development of theory and mathematical techniques used to form images from radio observations. These techniques underpin all of radio astronomy imaging today as well as extending to fields as diverse as medical imaging.

In themselves, each of the individual contributions is remarkable. However, even more remarkable is the fact that they evolved from one group, working in Australia immediately after World War II (WWII). At that time Australia had a population of just over seven million people and none of the Australian Universities even offered PhD-level qualifications. The technology trigger for this rapid period of development was the development of radar during WWII. This provided the technical foundation on which the *Four Pillars* flourished under the scientific leadership of Pawsey. While there have been enormous individual contributions in the development of radio astronomy and, in some cases, these have been recognised with the Nobel Prize, the summed contribution of the *Four Pillars* is equally significant and certainly not as well shared or understood. The legacy created by the *Four Pillars* is widespread not only in radio astronomy but also in fields as far reaching as the development of Wi-Fi. The story contains many remarkable elements including lessons on the process for creating environments in which research can flourish.

The aim of this book is to share this story with a wider audience with an interest in astronomy and science. Chapter 2 provides an introduction to the science of radio

astronomy and a brief background to the history of development leading up to the formation of the CSIRO Radiophysics Laboratory in Sydney, Australia. The subsequent chapters introduce each of the *Four Pillars*.

Chapter 7 discusses the influences that the *Four Pillars* had not only on radio astronomy but more broadly on other sciences and on engineering. We conclude with a discussion of the environment and leadership that led to this remarkable period of scientific development and the implications for research today. In drawing these together, we have a story which provides the foundations for the Australia Telescope, Wireless LAN developments, the Square Kilometre Array (SKA) and significant contributions to all the large international radio astronomy facilities operating in the twenty-first century.

We wish to thank the many people we had discussions with during the preparation of the memoirs and of this book: Mark Bracewell, Wendy Bracewell, Ron Ekers (FRS), David Ellyard, Ellen Bouton, Tim Christiansen, Larry D'Addario, Kent Price, Anne Green, Bob Hewitt, Claire Hooker, Crys Mills, Laurel Davidson, Bob Hayward, John Brooks, Mal Sinclair, Anne Manefield, Christine van der Leeuw, Lewis Ball, Dick Hunstead, Ken Kellermann, Bob Lash, Bruce McAdam, Wayne Orchiston, John O'Sullivan, Hastings Pawsey, Martin Y. Smith, Ron Stewart, Dick Thompson, Jasper Wall, Woody Sullivan, the late Sally Atkinson and Stephen White. Special thanks for extensive, detailed comments on the entire text to Tania Burchell, former assistant director of the National Radio Astronomy Observatory for Education and Public Outreach, and Professor Nicole Gugliucci of Saint Anselm College Department of Physics.

The authors thank Robyn J. Harrison for her expert editing, often at the last moment, as well as valuable advice.

We made extensive use of the University of Sydney Archives, the National Archives of Australia, the National Radio Astronomy Observatory Archives as well a number of interviews recorded by Woody Sullivan and R. Bhathal. We are grateful to the CSIRO for images provided courtesy of the CSIRO Radio Astronomy Image Archives and particularly the help of Jessica Chapman. We also wish to thank the Royal Society, the *Historical Records of Australian Science* and *The Journal of Astronomical History and Heritage* for permission to use material published in the memoirs of the *Four Pillars*.

Finally we thank the CSIRO for assistance during the publication of this book. Both Dr Douglas Bock and his predecessor, Dr Lewis Ball, (Director of CSIRO Astronomy and Space Science and Director of the Australia Telescope National Facility) have been enthusiastic supporters in providing funds for the editorial tasks during the last few years.

Lindfield, NSW, Australia — R.H. Frater
Socorro, NM, USA — W.M. Goss
Vaucluse, NSW, Australia — H.W. Wendt

References

Frater, R. H., & Ekers, R. D. (2012). John Paul Wild AC CBE FAA FTSE. 17 May 1923–10 May 2008. *Biographical Memoirs of Fellows of the Royal Society, 58*, 327–346.

Frater, R. H., & Goss, M. W. (2011). Wilbur Norman Christiansen 1912-2007. *Historical Records of Australian Science, 21*, 215–228.

Frater, R. H., Goss, M. W., & Wendt, H. W. (2013). Bernard Yarnton Mills AC FAA 8 August 1920–25 April 2011. *Biographical Memoirs of Fellows of the Royal Society, 59*, 215–239.

Thompson, A. R., & Frater, R. (2010). Ronald N. Bracewell: An appreciation. *Journal of Astronomical History and Heritage, 13*, 172–178.

About the Cover

The pier with Bob Frater's signature and cutouts of the other signatures that appear on other piers

In 1955, Australian radio astronomer Ron Bracewell, one of the *Four Pillars*, joined the faculty of Stanford University in California. There he established a Radio Astronomy Institute and developed an observatory. He built an array for solar observations using 32 ten-foot-diameter dish antennas, each of which was mounted on a concrete pier or pillar. Bracewell invited visiting astronomers to chisel their names into a pier, accumulating some 220 "signatures" over the course of 20 years.

In 1980, after two decades of use, the antenna array was closed. In 2012, ten of the piers were sawed off and shipped to the Karl G. Jansky Very Large Array in New Mexico to become part of a unique sundial designed by W.T. Sullivan III. As a tribute to radio astronomy, the markers of the sundial show not only the time of day and time of year but also the current location in the sky of Centaurus A, Cygnus A and Cassiopeia A, three prominent and important objects for radio astronomers.

The cover photograph is a small section of the sundial, with one of the antennas of the Array in the background. The *Four Pillars* (as well as the first author of this book and Joseph Pawsey, "the Grand Old Man of Radio Astronomy") had each signed one of the piers of the Stanford Array. Their signatures can be found on the pillars of this sundial.

Contents

1 Introduction 1

2 Beginnings: Some Basics and Some History 7

3 Bernie Mills: Cross-Type Telescopes and Discrete Radio Sources . . . 23

4 Chris Christiansen: Telescope Design and Earth-Rotational Synthesis 59

5 Paul Wild: Radio Astronomy and the Sun 91

6 Ron Bracewell: Mathematics and Imaging 131

7 Influences of the *Four Pillars* Beyond Radio Astronomy 153

8 Conclusions 167

Appendix A: What Is a Radio Telescope? 169

Appendix B: Paul Wild: The Beer Disaster of November 1957 181

Appendix C: Supercomputing Cluster 183

Appendix D: Time Line of Key Events 185

Appendix E: Dramatis Personae for *Four Pillars of Radio Astronomy* 189

Appendix F: Abbreviations 193

Index 195

Chapter 1
Introduction

The Significance of the *Pillars*

On 23 September 2013, the Ron Bracewell Radio Sundial officially opened near the visitor centre at the site of the Karl G. Jansky Very Large Array in New Mexico, USA. This unique instrument was designed by Woody T. Sullivan III and funded by donations from the Friends of the Bracewell Observatory and Associated Universities, Inc. The pillars of the sundial are the concrete piers that originally supported the dishes of the crossed-grating array that was built by Bracewell at Stanford. Over the years, these piers were used as a type of "guestbook", where Bracewell invited visiting radio astronomers to chisel their names into the concrete piers (see Fig. 1.1).

During the two decades until the observatory closed in 1980, over 220 signatures were collected on the piers forming a who's who of the pioneers of early radio astronomy. Ten of the original piers have been preserved and now form part of the new Radio Sundial (see Figs. 1.2 and 1.3). The design of the Radio Sundial is unique as it functions not only as a conventional sundial, but also allows visitors to locate the approximate positions in the sky of three discrete radio sources (Centaurus A, Cygnus A and Cassiopeia A) that played important roles in early radio astronomy. This creation is a fitting tribute to Bracewell who developed many of the mathematical techniques that are used in imaging by radio telescopes like the Karl G. Jansky Very Large Array visible in the background of the cover photograph.

While over 200 names appear on the piers of the Radio Sundial, in this book we have chosen to focus on four: Bernie Mills, Chris Christiansen, Paul Wild and Ron Bracewell. They were unique as they started their journey in a small team immediately after WWII under the mentorship of Joe Pawsey. They would go on to establish worldwide reputations as the leaders in their fields, and the instruments and techniques they developed would underpin much of modern radio astronomy.

R.H. Frater et al., *Four Pillars of Radio Astronomy: Mills, Christiansen, Wild, Bracewell*, Astronomers' Universe, DOI 10.1007/978-3-319-65599-4_1

Fig. 1.1 Ron Bracewell touching up the signatures chiselled on one of the concrete piers at Stanford

Australia Helps Lay the Foundation for Radio Astronomy

How such a concentration of scientific talent formed, particularly in a field of fundamental science and in a relatively isolated country like Australia immediately after WWII, is worthy of consideration. The necessity of developing radar in Australia during WWII was the catalyst for the formation of the Radiophysics

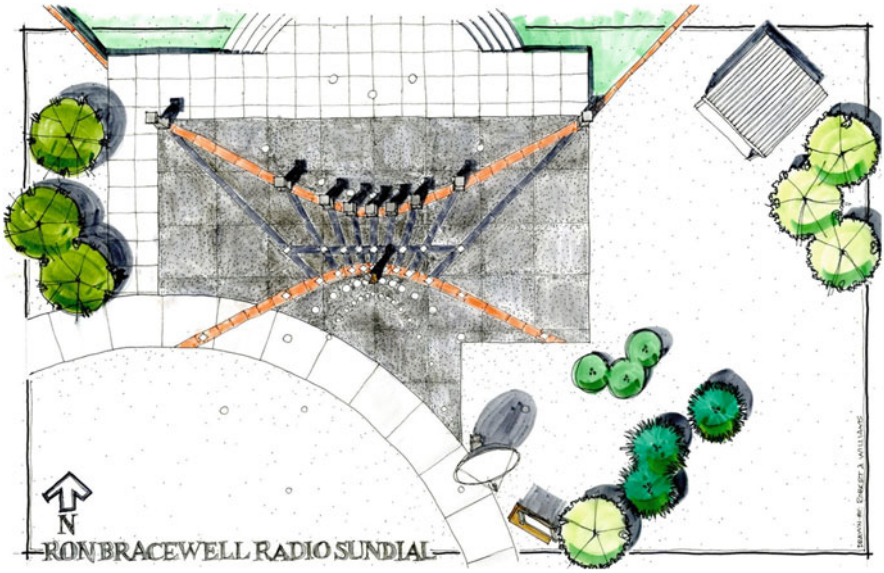

Fig. 1.2 A schematic plan of the Ron Bracewell Radio Sundial located at the Karl G. Jansky Very Large Array in New Mexico, USA, showing the configuration of the piers from the original crossed-grating array. Nine of the piers make up the markers of the Radio Sundial, with the tenth pier supporting a restored version of a dish from the original Stanford crossed-grating array (*lower centre*)

Laboratory (RPL) of the then Council for Scientific and Industrial Research (CSIR, later to become the Commonwealth Scientific and Industrial Research Organisation (CSIRO)). The leadership of Sir David Rivett, who held a strong philosophy of supporting basic research and finding the best individuals and giving them their head, established a culture that supported the early development of radio astronomy. Unlike both the USA and the UK, Australia did not have strong university research programmes underway to which the wartime radar researchers could return following the cessation of hostilities. Rivett's decision to retain the radar research team, but to refocus its activities on peacetime research, was key to forming what would be the largest radio astronomy research team in the world in the 1950s.

Another key factor was the unique marriage of the entrepreneurial leadership style of Taffy Bowen, who took over as Chief of Radiophysics in 1946, and the scientific leadership of Joe Pawsey, head of the radio astronomy group. This powerful combination, with Bowen playing the role of the outward charismatic leader of the Radiophysics Division, coupled with Pawsey's deep physical scientific understanding and his mentoring approach, set up a unique environment where researchers, including the *Four Pillars*, could flourish.

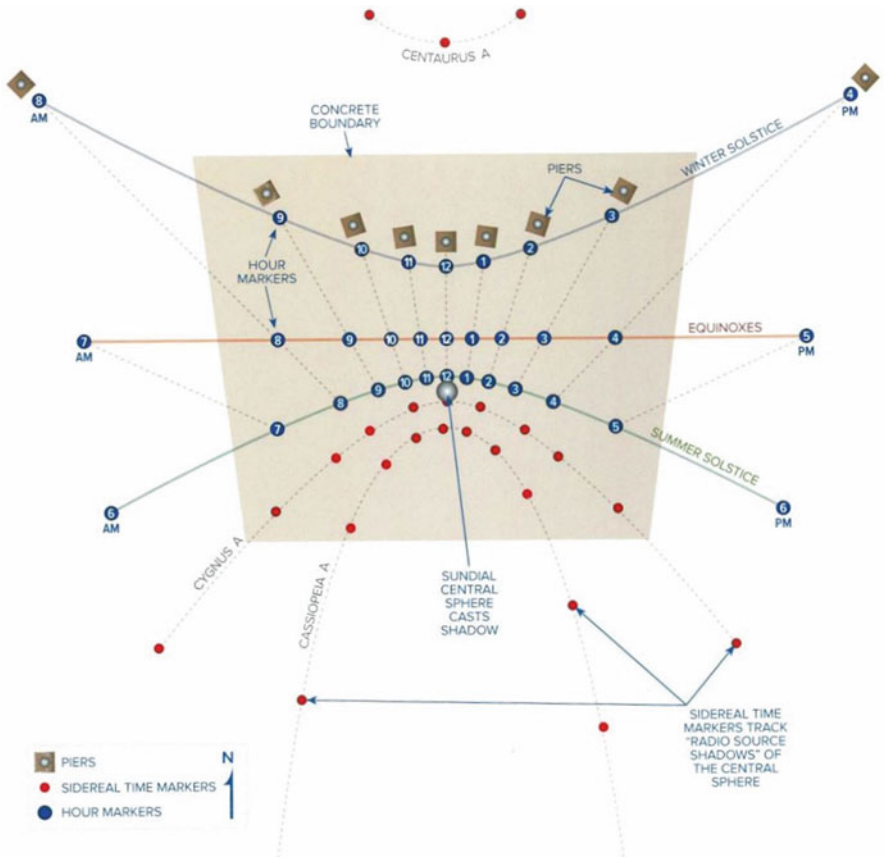

Fig. 1.3 A plan of the Bracewell Radio Sundial showing the locations of the piers and central gnomon, which is the part of a sundial that casts the shadow. The sundial can also be used to locate the position in the sky of three key discrete radio sources. The *red dots* mark the sidereal time of the radio source shadows (if they were visible). By standing on a marker close to the current sidereal time and looking back towards the gnomon sphere, the viewer will see the approximate position in the sky of the radio source (Courtesy of NRAO)

Pawsey (see Fig. 1.4) emphasised "research teams", rather than the efforts of individuals; this structure resulted in harmonious personal relationships among members of the team.

Frank Kerr (1963), one of the first appointees at RPL from early 1940, has written:

> Pawsey built up a powerful group which has made major contributions to almost every branch of radio astronomy. . .He was an inspiring research leader, with a particular skill in developing the independence and self-reliance of the members of his team to a point where many of them have achieved substantial reputations of their own. He expected his men to live up to his own high standards in their work.

Fig. 1.4 Joseph Pawsey in 1957 (Courtesy of Pawsey family collection)

Pawsey (1961) described the necessary ingredients for successful discovery:

> It should be noted that [this process] can only be followed effectively in a well-organized scientific organization in which the scientific direction can very quickly make decisions and supply facilities for the really promising developments. In all too many cases elsewhere, the energies of scientists are taken up in advertising the potentialities of their prospective investigations in order to obtain any support at all. The result is a neglect of the unspectacular preliminary probing investigations which are often such a vital ingredient in success.[1]

This book is about four men, Bernie Mills, Chris Christiansen, Paul Wild and Ron Bracewell, who were allowed their "unspectacular preliminary probing investigations" in this rich, nurturing environment. They rose up as pillars to support this

[1] Frank Kerr later wrote (1984): "[In Pawsey's group] simple equipment lead to the development of more and more complex equipment in a step-by-step manner as each stage produced new phenomena that needed to be elucidated".

new branch of astronomy, each in his own right, making important contributions to the theory and practice of observing the universe through the radio spectrum, a science that had its beginnings with the discovery by Karl Jansky in 1931 of radio waves coming from space.

References

Kerr, F. J. (1963). Joseph Lade Pawsey. *Quarterly Journal of the Royal Astronomical Society, 4*, 317–319.

Kerr, F. J. (1984). Early days in radio and radar astronomy in Australia. In W. T. Sullivan (Ed.), *The Early years of radio astronomy: Reflections fifty years after Jansky's discovery*. Cambridge: Cambridge University Press.

Pawsey, J. L. (1961). Australian radio astronomy: How it developed in this country. *Australian Scientist, 1*(iii), 181–186.