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Excerpt
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1 • Prologue

1.1 A NEW SKY

> My own suspicion is that the universe is not only queerer than we suppose, but queerer than we *can* suppose.[1]

British biologist J. B. S. Haldane penned this aphorism in the 1920s. Two decades later, in a 1948 popular article, he cited new results on radio noise from the sun as an example of what no one had imagined, with undoubtedly "much queerer things" to follow.[2] Casting over millennia, he talked of how people had first looked to the heavens as a source of heat and light, as well as of religious beliefs and astrological guidance. Later, they made other connections with the sky, such as the ocean tides and meteorites. And now, he argued that radio waves were of similarly great "philosophical importance." Haldane overstated the case, but there is no doubt that the coming of the radio telescope in the mid-twentieth century fundamentally shifted how extraterrestrial realms were viewed. It was not unlike the situation in the seventeenth century when the natural philosopher Robert Hooke remarked that the (optical) telescope had led to

> a new visible World discovered to the understanding. By this means the Heavens are open'd, and a vast number of new Stars, and new Motions, and new Productions appear in them, to which all the ancient Astronomers were utterly Strangers.[3]

Hooke also emphasized that this new world could only be attained by the "adding of artificial Organs to the natural." In this spirit, and jumping ahead three centuries, let us imagine a being with a radio antenna instead of eyes – call him *Homo radio*. What new aspects of the sky did he come to know after a decade of radio astronomy following World War II? How striking were they?

Figure 1.1 illustrates several startling differences from the familiar optical (or visual) sky, which of course was all that had been known for millennia. The signals received with *Homo radio*'s antenna, at wavelengths roughly one million times longer than those in the optical band, would be noise-like radiation first called *cosmic noise* – "noise" because when detected and impressed on a loudspeaker, it would sound like the *shhhh* heard on an analog radio or television channel when the station is *not* broadcasting.[4] The only information to be gained as he scanned the sky at a given frequency would be the intensity of the radio noise at different locations. Hooke's contemporary Blaise Pascal had been frightened by the eternal silence of infinite space,[5] but now the heavens were full of "mysterious sounds, a haunted Universe forever emitting ghost-like wails."[6]

Homo radio's sky would be seen at any time of day or night, through clouds or rain – very different from optical astronomy.[7] Radio astronomy was sometimes even called "blind astronomy":

[1] J.B.S. Haldane (1927), *Possible Worlds and Other Essays* (London: Chatto & Windus), p. 286 in "Possible Worlds."

[2] Haldane, "Radio from the sun," *Daily Worker*, p. 2, 16 February 1948. Haldane was inspired to write this article after hearing a paper at the Royal Society, later published by Ryle and Vonberg (1948).

[3] R. Hooke (1665, London), *Micrographia*, quotes from the Preface.

[4] *Noise* is a technical term in physics and engineering, confusing because it is used for much more than sound waves, in fact for any signal characterized by random fluctuations. In early radio astronomy it could refer to the desired radio signal (as in *cosmic noise* or *solar noise*), or just as well to competing noises from the sky or from receiver electronics (see Sections A.8 and A.9 for further explanation).

[5] "Le silence éternel de ces espaces infinis m'effraie." [Pascal (1623–1662, *Pensées*)]

[6] W. L. Laurence, "Radar yields new world of sound; brings 'music of spheres' to Earth," 6 October 1948, *New York Times*, p. 1.

[7] If *Homo radio* had happened to live on a permanently beclouded planet, then this view would have been the *only* available one of

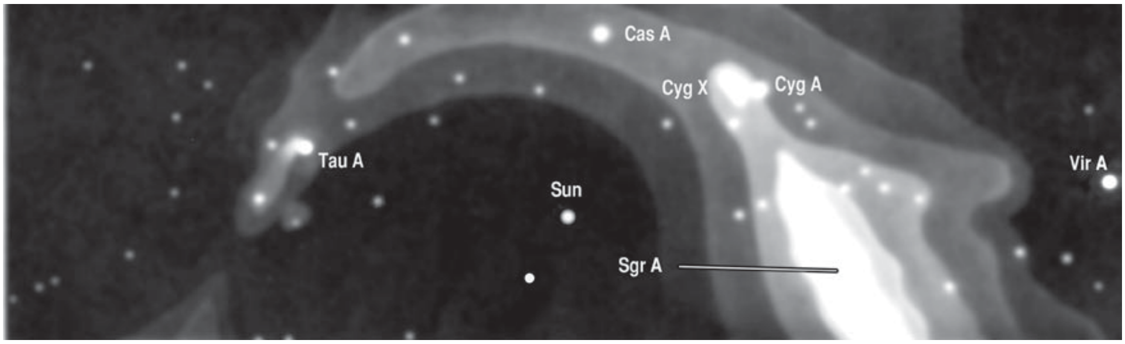

Figure 1.1 The northern sky as seen with "radio eyes." The map extends from –40° to +70° in declination; north is up and east to the left. This artistic rendering is based on a map, observed with a beam of 1° × 8° at a frequency of 250 MHz (wavelength of 1.2 m), taken with a helix array at Ohio State University in the mid-to-late 1950s. The broad curving band, defining the radio Milky Way, corresponds in position to the optical Milky Way (the galactic plane). The position of the radio sun varies through the year and is shown for the spring equinox; its intensity also varies greatly on various time scales, but normally is far fainter than the radio Milky Way. The strongest radio stars are labelled (see Table 14.1 for details of sources); Cyg X is a large, diffuse region and Sgr A, the galactic center, is lost in the surrounding region of strong emission.

> The biggest telescope in the world now stands on a site near (of all places) Manchester [England]. Here its 200 ft reflector gazes blindly upwards, heedless of mist and cloud and even of daylight.[8]

The siting of radio telescopes was thus not as critical as for optical telescopes (although manmade radio interference could be a problem), a fact that brought British and Dutch astronomy into renewed prominence in defiance of their rainy homelands.

Homo radio's sun, although a strong emitter, would be vastly outshone (especially at the lowest frequencies) by a broad band of radio Milky Way stretching across an otherwise dark sky (also see Fig. A.5).[9] His main sources of illumination would be neither sun nor moon, but this Milky Way swath, with a strong concentration toward the constellation Sagittarius. And if our creature tuned his radio receiver to the specific frequency of 1420.4 MHz, the entire sky would take on an additional radio glow, girdled by a thinner Milky Way strip.

"Radio daytime" would correspond to when the brightest and largest part of the Milky Way was above the horizon, and have nothing to do with the sun – but even in this "daytime" most of the sky would be dark. Moreover, the contrast between day and night would be far less than we optical beings experience. At shorter wavelengths, a very faint radio moon, complete with phases, would shine. Strikingly, the radio sun, rather than shining steadily, would sometimes suddenly become thousands of times brighter than usual, and on rare occasions millions of times brighter. These outbursts would usually last seconds or minutes, but sometimes persist for days in groups called "noise storms." Rather than a simple *shhhh*, these sounded like "a combination of gravel falling on the roof and the howling of wolves"[10] – this was no music of the spheres!

Scattered around the sky (not unlike at optical wavelengths) would be hundreds of discrete *radio stars*,

the universe, at least until rockets and satellites could breach the clouds and gain access to optical and other wavelengths (see Section 18.2).

8 "An unsuspected universe revealed," *The Times* (London), 4 October 1952, p. 7. (The mentioned reflector was the Jodrell Bank fixed dish of 218 ft diameter [Section 9.3].) The term "blind astronomy" was first used by P. M. S. Blackett, during a Royal Astronomical Society meeting in Manchester on 1 July 1949 [*Observatory* **69**, 122 (1949)]. Also see note 17.31.

9 In 1959 optical astronomer Otto Struve called this fact "one of the most sensational discoveries in astronomy during the present century" [MIT Compton Lectures, as published in *The Universe* (1962) (Cambridge: MIT Press), p. 98]. At a frequency of 20 MHz the total radio radiation from the Milky Way is ~10^4 times more than that from the (quiet) sun; the comparable ratio at optical wavelengths is 10^{-8}.

10 As in note 6; quotation from D. H. Menzel.

the brightest handful (Fig. A.2) comparable to the quiet sun, but without the huge bursts. Each radio star would appear as an ill-defined, fuzzy blob on the sky, not a pinpoint of radiation. *Homo radio* would realize that this was due to an inherent defect in his antenna apparatus, but for technical reasons would not yet be able to create sharper radio images except for the few strongest radio stars. Some of the radio stars would twinkle (or scintillate) in their intensity; at first it would not be clear whether these changes were intrinsic to the radio stars or caused by the earth's atmosphere.

After ten years of applying powerful physics and mathematics, what would *Homo radio*'s theoretically minded colleagues make of all this, even if we should grant them full knowledge also of the optical sky? The biggest quandary would be what to do with the radio stars, for, despite their name, not a single radio star's position on the sky agreed with positions of the bright optical stars, although a handful agreed with the positions of faint, peculiar optical nebulosities. The only consensus as to mechanisms of emission would be (a) the bright glow at 1420.4 MHz arose from ubiquitous cold hydrogen atoms, and (b) the quiet sun's radio emission originated in a hot coronal gas surrounding the sun. All other explanations would be tentative. As one early radio astronomer later recalled this situation:

> There appeared to be an optical universe and a radio universe which were utterly different, which coexisted. So there was obviously a need to tie them together somehow.[11]

And one early textbook of radio astronomy flatly stated:

> The primary source of radio waves in the universe is not known; it is probable that [optical] stars supply only a small fraction of the total.
>
> (Pawsey and Bracewell 1955:210)

This remarkable sky posed numerous puzzles even as it led to expanded views of many old astronomical questions. It not only created a new sky, but necessarily meant that the previously known sky now became an *optical* sky. There were now *two* ways to view the heavens. Indeed, another important effect of the establishment of radio astronomy was to create *optical* astronomy, *optical* astronomers, and *optical* telescopes.

In the following section, I lay out the overall structure of the book and summarize my basic narrative for early radio astronomy, as well as explaining the rationale for an ending point of 1953. In Section 1.3 I discuss my approach to history, compare this study with other treatments of the field, and lay out the four major historical themes of the book. These deal with the profound influence of World War II and the Cold War on the development of the field; the field's intimate entanglement of technology and science; early radio astronomers' ironic drive toward a "visual culture" in terms of their quest for tie-ins with astronomers and their (optical) sky; and finally, radio astronomy as the twentieth century's New Astronomy, one of the key developments in the millennia-long history of astronomy.

1.2 ORGANIZING THE STORY

1.2.1 Defining radio astronomy

Before relating a narrative, I must first define "radio astronomy." The question is vexed because there is the danger of engaging in "tunnel history," in which the standards of a later time, in this case how science organizes itself into research areas and disciplines, are imposed on an era that did not know them. To avoid such an ahistorical exercise, I tell the story in terms that would be understood by the participants at any given time, to allow the reader to experience the world-picture (*Weltbild*) of that day. To do otherwise might cause us to miss fascinating and insightful aspects of the history, in particular the decade-long transition from (1) disparate physicists and radio engineers (with a few astronomers) making discoveries about the earth's ionosphere, the sun and moon, the Milky Way, and beyond; to (2) a research community of "radio astronomers" who, although still distinct from traditional astronomy, were slowly becoming integrated. Note, however, that the term *radio astronomy* did not have currency until 1948–49 (and *radio astronomer* even later[17.2.1],[12]), so

[11] J. G. Davies (1971:40T), also cited by Edge and Mulkay (1976:268). The notation "Davies (1971:40T)" is explained at the end of Section 1.2.2.

[12] In the remainder of this chapter, superscripts of the form [X] indicate that Chapter or Section X contains the relevant topic. The book's organization, key episodes, and main arguments can also be telegraphically followed using the Annotated Table of Contents.

how can one legitimately talk about a history of radio astronomy beforehand?

My approach to this conundrum is akin to that of Good (2000), who dealt with the same issue when analyzing the development of geophysics before 1900, at which time the term *geophysics* and a discipline began to emerge. He discusses an "assembly" of geophysics at that time from components contributed by many fields and recombined in various ways. Thus I also will follow the story of the motley components before 1948 that were eventually to emerge as something called radio astronomy (although I will argue that this emergence was not as a separate discipline, but as a research specialty).[17.2.5] These components included trans-Atlantic radio telephony, studies of the ionosphere and its effects on communications, military radar development during and after World War II, radio waves from the quiet and active sun, radar reflections from meteor trails and from the moon,[13] sky surveys with various antennas and receivers, special studies of regions of discrete emission (radio stars), and (optical) astronomical studies of Milky Way rotation.

1.2.2 Structure of the book

The book relates activity before World War II in Chapters 2–4, the wartime discovery of the radio sun in Chapter 5, and in Chapters 6–10 the beginnings, first major results, and distinguishing characteristics of each major group. Chapters 11 and 12 examine the subfields that studied meteors and the moon via radar reflections. Chapters 13 through 16 then follow in detail, through ~1953, the development of each major radio astronomy topic: the sun, radio stars, theories of galactic noise, and 21 cm hydrogen-line studies of the interstellar medium and Galaxy. Chapter 17, "New astronomers," is a detailed historical analysis of various aspects of early radio astronomy. Topics include its origin in war, the watershed in its character circa 1952–53, interactions between radio and (optical) astronomers, whether or not it was a new discipline, national and Cold War influences on how the field developed, and the role of technology. Chapter 18, "A New Astronomy," summarizes the new science that emerged from radio astronomy and appraises where radio astronomy fits in the larger history of astronomy. In particular, Section 18.2 briefly relates for comparison the openings after World War II of each of the *other* spectral windows: infrared, ultraviolet, X-ray and γ-ray (summarized in Table 18.1). Radio astronomy preceded and paved the way for these. Finally, I argue that the appearance of radio astronomy (or more broadly, the opening of the entire electromagnetic spectrum) was not a "revolution" as historians usually define it, but more a transformative event, a *New Astronomy*, similar in nature and importance to earlier major developments in the long history of astronomy. The issues of Chapters 17 and 18 are further introduced in Section 1.3.3.

In the back matter, Appendix A is a primer on the techniques and astrophysics of early radio astronomy (with its own index of terms) for readers who would like to learn more of the basic science and engineering involved in early radio astronomy. Appendix B discusses many aspects of interviewing and how it was done for this history, as well as listing the interviews conducted during this project. Appendix C gives details of the archival sources that I consulted and acts as an index for the three-letter codes (e.g., GRE, RPS) seen at the end of archival citations in footnotes. Tangent 1.1 (at the end of this chapter) discusses conventions in this book (such as using the unit MHz when describing Jansky's work, although he used Mc/s). "Tangents," located at the end of individual chapters, include peripheral topics and technical details. Finally, besides the Index, note that the References list, which is arranged chronologically, also acts as an index in that each listed item includes the primary page(s) where the item is discussed. The References list gives full information for all items cited in the text with "Jones (1950)" or Jones (1950:472) formats (the latter referring specifically to p. 472). Quotations from interviews are cited with the formats "Smith (1976:14T)", "Smith (1976:107B:420)" or "Smith (1976:2N)," each referring to a 1976 interview with Smith (see Appendix B for details).[14]

[13] At a later stage the term *radar astronomy* came to be applied to astronomical studies involving radar reflections. However, during the period of this book (before 1953), meteor and lunar radar studies were considered aspects of radio astronomy. For example, the term *radar astronomy* does not appear in two early books on radio astronomy despite their extensive chapters on radar techniques and results (Lovell and Clegg 1952; Pawsey and Bracewell 1955).

[14] Additional information relating to the topics and specifies of this book is available at www.astro.washington.edu/woody.

1.2.3 Narrative summary

Here I present a précis of my narrative, which extends through ~1953, a year that was a watershed for radio astronomy for several reasons.[17.1.2] By that time the bulk of the radio astronomers were no longer astronomical novices, at a mid-career stage in their 30s, and some even recipients of significant professional honors. Furthermore, integration with astronomy as a whole was gaining strength; for instance, to aid communications, the radio astronomers at this time officially voted to discourage use of terms like *solar noise* and *cosmic noise* (as in this book's title) in favor of *solar radio emission* and *galactic radio emission*. In addition, the field's most important sectors had migrated from solar to galactic and extragalactic questions (although solar research still quantitatively dominated). The first two textbooks of radio astronomy also appeared about this time. Finally, the field was moving from empirical exploration to a more programmatic approach, entailing enormous antennas whose correspondingly larger budgets meant that they could no longer be built in-house by the individual groups. Radio astronomy was moving into a Big Science phase.

Figures 1.2 and 1.3 illustrate the broad flow of the history by following, respectively, the major groups and the primary research subjects through ~1953. These charts should be consulted while reading the following narrative. In addition, Tables 10.1 and 11.1 present basic data for each of the postwar groups in radio and radar astronomy. Almost all of this research was a direct outgrowth of the development of radar and other radio techniques for myriad military purposes during World War II. Radar research and development during the war was huge, second (in the US) only to the atomic bomb project. Its importance to the war effort, caricatured in Fig. 1.4, was sometimes expressed as "The atom bomb only ended the war; radar won it" (Kevles 1977:308).[5.1, 17.1.1]

Although the first detection of extraterrestrial radio waves was not until 1932, in the period 1894–1901 there were several attempts in Europe to detect Hertzian (radio) waves from the sun.[2] Yet in the ensuing four decades, as radio technology steadily improved, no one made serious attempts to detect the sun. This was because of a lack of sensitive, directional radio equipment, discipline specialization, and a reliance on Planck's blackbody theory (1900) to calculate expected signal levels. So it was that Karl Jansky, a radio physicist working at the Bell Telephone Laboratories in New Jersey, only serendipitously discovered extraterrestrial radio emission in 1932 – and it came from the Milky Way, not the sun.[3] With his beam size of ~30° at a frequency of 20 MHz, he established that the emission (he called it "star static") was strongest toward the center of our Galaxy, yet appeared all along the galactic plane.

The hard times of the economic Depression and the bizarre nature of Jansky's discovery meant that, although his results were generally known, little serious follow-up occurred throughout the 1930s. The lone exceptions were investigations carried out over a decade by radio engineer Grote Reber.[4] Living in a Chicago suburb, in his spare time and with his own funds, Reber took it upon himself to build a 31 ft (9.4 m) diameter dish in his backyard in order to check Jansky's findings at much higher frequencies. He ended up making two maps over the northern sky of what he called "cosmic static" (Fig. 4.7). Along the way, Reber also detected solar radio emission (but did not know of earlier unpublished work by others) and established working relations with the astronomers at Yerkes Observatory. Yet despite this pioneering and ingenious work through 1947, Reber had little influence on the postwar development of radio astronomy, especially outside of the US.[4.7]

The man who was seminal for the beginnings of radio astronomy in England was Stanley Hey. As a radar-operations researcher during the war, in 1942 he deduced that apparent jamming of British coastal radar installations was in fact radio radiation picked up from the sun.[5.2] This was the earliest conclusive detection of the radio sun (and kept secret until war's end), although before the war amateur radio operators and ionospheric physicists had garnered some evidence of the same.[5.4] Later during the war, the sun was independently studied by George Southworth of Bell Telephone Labs at centimeter wavelengths,[5.6] as well as detected during wartime operations in Germany and in New Zealand.[5.3]

Before the end of the war, Hey also encountered and investigated both the Jansky/Reber galactic noise and anomalous echoes that he determined originated from the ionized trails of meteors.[6.1] Until the Cold War heated up in 1948, Hey was able to hold together his small Army group and conduct significant research

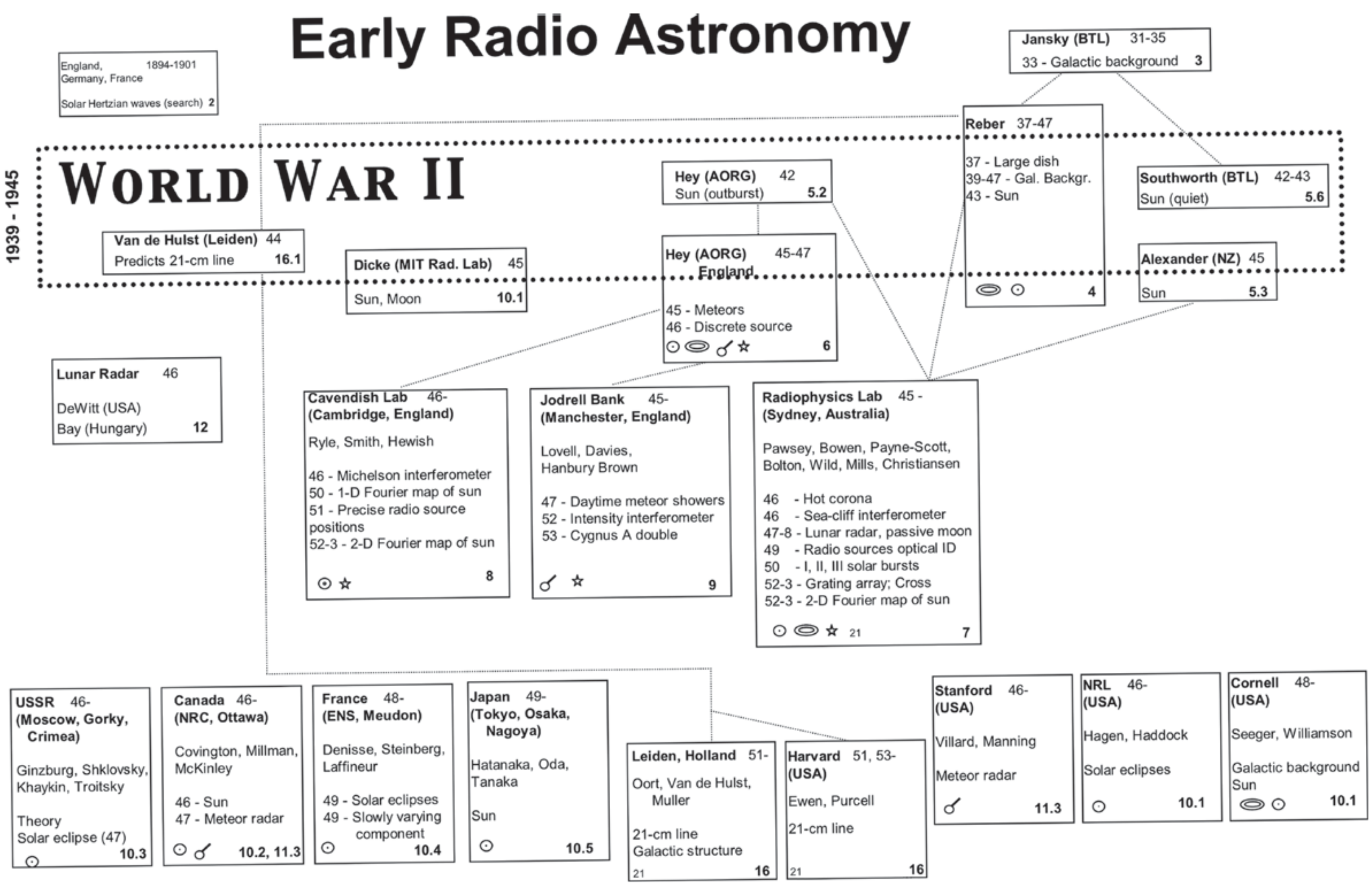

Figure 1.2 The development of early radio astronomy tracked via major groups and persons. Research highlights in each box are incomplete and emphasize the earlier years. Dates are indicated by, for example, 45 = 1945. The boxes are arranged to show a rough chronology; in particular note their placements and extents relative to the large World War II box. Connecting lines indicate direct influences on the origin of a group. Symbols at the bottom of each postwar box indicate to which of five main subfields a group contributed: for example, at the bottom of the "Hey (AORG)" box, the symbols represent (l. to r.) the sun, galactic background radiation, meteors, and radio stars. The fifth subfield symbol is "21" for 21 cm hydrogen line study. Bold numbers in the lower-right corner of each box refer to chapters or sections where each group is discussed.

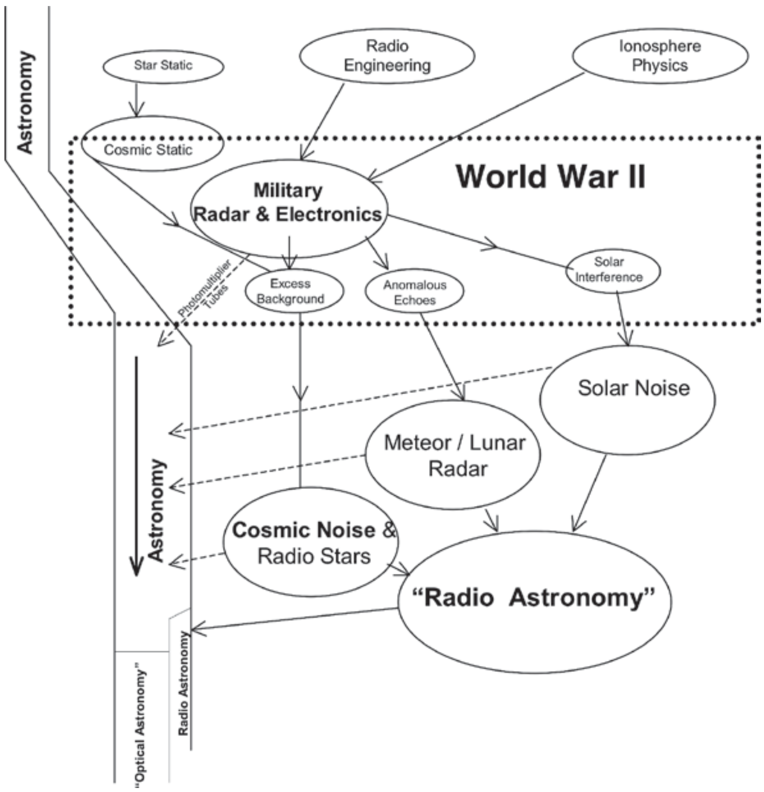

Figure 1.3 The development of early radio astronomy tracked via subject areas. Note the primacy of military radio and radar electronics and engineering, as well as the influence of ionosphere physics. Note also the secondary influence of Jansky's star static and Reber's cosmic static, along with the influences of wartime anomalous radio phenomena, two of which J. S. Hey discovered, that led to the three primary postwar areas of inquiry. These in turn became "radio astronomy" in 1948–49, which eventually joined the ongoing astronomy "stream," although keeping its own identity. Later came the newly defined "optical astronomy" (see Section 17.2). The photomultiplier tube's effect on postwar optical astronomy is discussed in Section 17.2.2.

in all aspects of radio astronomy, most importantly establishing the existence of the first discrete "radio star," later known as Cygnus A.[6.2]

Two other major postwar groups also began in England at this time as an outgrowth of radar research at the wartime Telecommunications Research Establishment. Martin Ryle started at the Cavendish Laboratory of Cambridge University in an ionospheric research group, but soon was investigating radio waves from the sun and radio stars, of which by 1949 his group had found 23 (including Cassiopeia A).[8] In the process he invented many techniques fundamental to radio astronomy, such as the Michelson interferometer and the phase switch, and assembled the core of a powerful research group featuring Graham Smith and Antony Hewish. The second British group, led by Bernard Lovell, studied radar echoes from meteor trails at Jodrell Bank, a field station of the Physics Department of Manchester University.[9] Over the postwar decade Lovell's group developed techniques to measure the trajectories and velocities of meteors and dominated the world in this field. For instance, new techniques enabled study of *daytime* meteor showers. In 1949 Lovell was joined by Robert Hanbury Brown, another leading wartime radar veteran. Hanbury Brown focused on using a huge fixed dish of diameter 218 ft (66 m), and with his student Cyril Hazard detected for the first time radio waves from an external normal galaxy, the Andromeda nebula.[9.3]

The largest of all the postwar groups was led by Edward "Taffy" Bowen and Joseph Pawsey of the Radiophysics Laboratory (RP), Sydney.[7] This

Figure 1.4 World War II cartoon showing the effects of radar on the Axis powers represented by cowering Hitler, Mussolini, and Hirohito. (Philco Co. advertisement, *Life* magazine, 9 August 1943, p. 3)

Australian laboratory was one of the world's premier wartime radar labs and remained intact after the war, switching its electronic know-how to investigation of cosmic noise. With Bowen's management skills and nose for good projects, and Pawsey's inspired scientific leadership of teams of radio engineers and physicists at field stations scattered around Sydney, RP developed techniques such as the sea-cliff interferometer and Fourier-synthesized maps. Basic discoveries in the early years included a hot radio solar corona at a temperature of 1×10^6 K (Pawsey and David Martyn)[7.3.3]; angular sizes of $<10'$ [15] for solar radio burst regions (Pawsey, Lindsay McCready, and Ruby Payne-Scott)[7.3.2]; motions and frequency-drift structure of solar bursts (Payne-Scott; Paul Wild)[13.2.1.2]; suggested identifications of three radio sources with optical objects: Taurus A with the Crab nebula (remnant of a supernova explosion), Centaurus A with a weird nebula catalogued as NGC 5128, and Virgo A with the distant elliptical galaxy Messier 87 (John Bolton, Gordon Stanley and Bruce Slee)[7.4, 14.1]; and pioneering measurements of radio source properties and distributions across the sky (Bernard Mills)[14.3.2, 14.4.1]. The success of the RP group was all the more remarkable given that Australia at this time was geographically and scientifically isolated, and not known for its science. The esteem of RP's colleagues can be gauged by the decision to hold the 1952 meeting of the International Union of Radio Science (URSI) in Sydney, the first time *any* major international scholarly society had met in Australia.

The story of early Dutch radio astronomy is anomalous in that it was not driven by radar veterans and in fact was directed by (optical) astronomers.[16] Upon learning of Reber's results, astronomers Jan Oort and Hendrik Van de Hulst, at Leiden University in occupied Holland, as early as 1944 considered the possibilities of using radio spectral lines to study the structure of the

[15] $60' = 60$ arcmin $= 1°$; the angular size of the sun is $32'$. See Section A.6 for more information.

Milky Way, a specialty of Oort's since the 1920s. Once the war ended, resources were scarce and radar veterans were nonexistent, but Oort persisted and eventually succeeded when he found Alexander Muller, a talented radio engineer fresh from undergraduate study. Muller built a receiver that in 1951 detected a spectral line of atomic hydrogen at a wavelength of 21 cm (closely following its discovery in the US [see below]). This technique made accessible an entirely new component of the interstellar medium. There quickly followed the first of many Galaxy surveys exploiting the line's Doppler shifts in order to detect spiral arms composed of cold hydrogen. An "international Dutch school" of 21 cm Milky Way studies was soon established.

Besides the above five major groups in the postwar decade, many other efforts sprung up around the world.[10] In the United States[10.1] Robert Dicke, a physicist at the Radiation Laboratory run by the Massachusetts Institute of Technology, the largest of the American wartime radar labs, developed his eponymous microwave receiver and with it in 1945 was the first to observe the moon and a solar eclipse. At the US Naval Research Laboratory (Washington, DC), another leading wartime radar lab, John Hagen's group, starting in 1946, undertook many solar projects at microwavelengths, including eclipse expeditions, and also built a 50 ft (15 m) diameter dish.[10.1.2] Smaller groups were at Cornell University[10.1.3] and Stanford University[11.3]. Finally, a one-time effort (a Ph.D. thesis project) represents the most significant US contribution to radio astronomy in the postwar decade. This was the discovery at Harvard University in 1951 of the 21 cm hydrogen line by physicists Harold Ewen and Edward Purcell (both former wartime radar experts).[16.3]

Radio astronomy in the USSR was strongest in theoretical studies and dominated from the start by physicist Vitaly Ginzburg (Lebedev Institute [FIAN], Moscow) and astronomer Iosef Shklovsky (Moscow State University).[10.3.1] In 1946 both made seminal contributions to solar coronal radio theory. From 1951 onwards, Ginzburg argued in detail for a connection between cosmic rays and the still-unexplained galactic background radiation, namely that relativistic electrons in the Galaxy's magnetic field copiously produced radio waves via the synchrotron mechanism.[15.4] Shklovsky worked out a theory for interstellar radio lines of hydrogen, hydroxyl (OH) and CH in a 1949 paper, and in 1953 suggested that *both* the enigmatic radio and optical radiation from the Crab nebula arose from the synchrotron mechanism.

In France, groups at the Ecole Normale Supérieure in Paris and Meudon Observatory undertook solar observations both at home and on eclipse expeditions to exotic locales.[10.4] Jean-François Denisse was a leader in solar radio theory and recipient in 1949 of the first doctorate awarded for a radio astronomical topic. Canada produced important observations of the sun[10.2] and of meteor echoes[11.3] and in Japan several isolated solar groups made contributions[10.5].

Study of the moon using radio techniques occupied a small but fascinating niche for a few years.[12] In early 1946 John DeWitt of the US Army Signal Corps in New Jersey led Project Diana, which marshaled a powerful transmitter to first detect radar echoes from the moon.

Meteor radar was a fruitful subfield during the postwar decade, although unique in early radio astronomy in that by the mid-1950s it had peaked and gone into decline.[11] There had been several studies before the war suggesting that the ionized trails of meteors could effectively reflect radio waves, but the effect was not confirmed until 1945 when Hey's group undertook a three-station triangulation experiment on anomalous echoes that had often been seen during wartime operations.[6.3] The October 1946 Giacobinid meteor shower, spectacular (as predicted) for visual observers, also represented a milestone for the many radar teams who were inundated with echoes.[11.2] The major scientific question to which meteor radar contributed was the issue of whether there existed a component of meteors arriving from interstellar regions, completely outside the solar system. Astronomers had been debating this issue for decades, and in the end statistics from huge numbers of echoes gathered at Jodrell Bank and in Canada convinced most that very few, if any, meteors had hyperbolic orbits indicative of interstellar origin.[11.4.2]

Studies of solar noise constituted fully ~70% of the efforts of early radio astronomers, and yet this was the subfield where the fewest fundamental astronomical discoveries were made.[13] Radio observers did, however, contribute important evidence for the million-degree corona that astronomers had been suspecting since the 1930s.[13.3.1] Tremendous efforts went into monitoring radio burst activity and correlating it with various optical properties – the main outcome was the recognition of a "slowly varying component," a long-term oscillation in total microwave intensity that followed the 11-yr sunspot cycle.[13.2.3] In other studies, expeditions were mounted to eight solar eclipses over the period 1945–52 (Fig. 13.6) in order to gain higher angular resolution by using the moon as a moving knife edge.[13.1.3] Perhaps the greatest contribution of the sun, so to speak, to radio astronomy was as a handy test bed for new high-resolution mapping techniques developed by Ryle at Cambridge and Wilbur "Chris" Christiansen in Sydney. By 1953 both groups had made two-dimensional maps of the sun using Fourier analysis of data gathered with interferometric portable antennas and grating arrays.[13.1.3, 13.3.2]

Radio stars, or radio sources as they eventually became known, were the central puzzle in early radio astronomy.[14] Four major surveys were carried out by the groups in Cambridge, Manchester, and Sydney over 1949–53,[14.3] but only about 5% of the ~250 known radio stars correlated with any optical object, i.e., had what became known as an "optical identification."[14.4] Furthermore, different surveys in areas of overlap often seriously disagreed (Fig. 14.5). Two astronomers with access to the world's largest telescopes, Walter Baade and Rudolph Minkowski, were central to taking the deep photographs required to make identifications, which then bolstered the degree of reality of any associated source. On the radio side, positions accurate to a few arcminutes or better were required for any chance at an identification; one particularly pivotal effort was the precision interferometry of Smith at Cambridge. Positional accuracy of $\sim 1'$ allowed the two strongest sources in the sky, which had stubbornly resisted previous attempts, finally to be identified with (a) a strange network of fast-moving filaments that was perhaps a supernova remnant (Cas A, Fig. 14.14), and (b) a faint, distant peanut-shaped object, taken to be a pair of galaxies in collision (Cyg A, Fig. 14.13). The latter especially was significant, for it implied that if Cyg A's intrinsic properties were at all typical, then the bulk of the *un*identified radio sources were at distances beyond what (optical) telescopes could explore. Thus did radio astronomy become relevant to cosmological inquiries at an early stage.[15.5] Together with the earlier identifications of Tau A, Vir A and Cas A, it was also clear that radio astronomers were revealing violent, high-energy regions hitherto unsuspected by (optical) astronomers.

Another desired measurement for a radio source was its angular size.[14.5] But the intrinsically poor resolution of most early antennas and interferometers made such observations a difficult task except for the strongest few sources. These turned out to have sizes of a few arcminutes, which argued that they were not radio *stars* at all, but *radio nebulae*. One novel technique for measuring sizes, the intensity interferometer, was developed at Jodrell Bank by Hanbury Brown and Richard Twiss. With it Roger Jennison and M. K. Das Gupta not only measured the angular extent of Cyg A, but found that it mystifyingly consisted of two blobs separated by $1.5'$, one on either side of the optical object.

The source of the galactic background radiation that Jansky had originally discovered, and its connection, if any, with the enigmatic radio stars, were vigorously debated in the postwar decade.[15] By 1953 there was still no consensus as to how radio power originated in radio stars and in the general background. One approach was to consider the background to be the integrated effect of a huge number of faint radio stars, but such a hypothesis implied that this new type of (radio) star was not confined to the galactic plane. Others considered radio stars to be very close-by and of low intrinsic power, whereas the background radiation originated either in hot gas or in cosmic ray particles. Soviet theorists in particular pushed for the synchrotron idea, but in the West it was little accepted until after the mid-1950s.[15.4]

By 1953, when the present history ends, we thus have a burgeoning and maturing field generating more questions than answers regarding the origins of the various types of celestial radio emission visible in Fig. 1.1. It was a revolutionary new sky, albeit with most radio sources (and the galactic background) still a mystery despite collaborations with (optical) astronomers that had yielded a handful of key optical identifications.

1.3 ANALYSIS

1.3.1 Earlier studies

The major prior study of the history and sociology of radio astronomy is *Astronomy Transformed: the Emergence of Radio Astronomy in Britain* (1976) by David Edge (1932–2003) and Michael Mulkay, the former a student of Martin Ryle's at Cambridge (Ph.D. in 1959)