**“The lucky start toward today’s cosmology”?**

**Serendipity, the “big bang” theory and the science of radio noise in Cold War America**

Kendrick Oliver\*

\*Department of History, Faculty of Arts and Humanities, University of Southampton, Southampton, SO17 1BF, UK; [ko@soton.ac.uk](mailto:ko@soton.ac.uk)

The following abbreviations are used: AT&T, American Telephone and Telegraph; ATTA, AT&T Archives and History Center, Warren, NJ; *BSTJ*, *Bell System Technical Journal*; CMB, cosmic microwave background; CRL, Columbia Radiation Laboratory; DP, Robert H. Dicke Papers, Princeton University Library; DPR, Department of Physics Records, 1870-1983, Rare Books and Manuscripts Library, Columbia University; HP, Martin Harwit Papers, Cornell University Library; JSEP, Joint Services Electronics Program; LC, Library of Congress; NSF, National Science Foundation; NRL, Naval Research Laboratory; NBLA, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD; ONR, Office of Naval Research.

ABSTRACT

The discovery of the cosmic microwave background radiation – an inflection point in post-war cosmology – has not lacked chroniclers, but few have drawn deeply upon the available archival record. Many accounts emphasize the serendipitous manner in which the radiation was detected. This article redefines the relative contributions of luck, skill and circumstance to the discovery by thickening the contexts in which it occurred. In its emphasis upon the material conditions of scientific enquiry, the development of technical expertise and the permeability of disciplinary boundaries, the article situates the discovery in the sort of explanatory context more familiar from histories of Cold War nuclear and electronics research, where funds flowed freely across a broad front of institutions and subject fields, underwriting innovation and exchange, and incentivizing the instrumentalization of basic knowledge to address real world problems: in this case, microwave radio noise. It was not research to resolve the “big-bang”/“steady-state” controversy that pulled the radiation within range of detection, but a protean technoscientific program to improve signal-to-noise ratios. The accumulation of proficiency in microwave communications at Bell Laboratories, where the radiation was detected, was as significant to the breakthrough as the expertise in theoretical astrophysics available at Princeton, where the Bell Labs measurements were linked to the “big bang”. Princeton physicists, led by Robert Dicke, had already embarked on their own independent effort to detect the radiation, but evidence suggests they may not have succeeded absent the instrumental contributions made by Bell Labs.

KEY WORDS: Serendipity, big bang, cosmic microwave background, cosmology, Robert Dicke, Arno Penzias, Robert Wilson, Bell Laboratories

Big science, little science: the case of post-war cosmology

Measured by the scope of its intellectual concerns, cosmology – the study of the large-scale structure of the universe - has always been a big science. But the more standard definitions of “big science” tend to emphasize the resources available to a research field and the resulting scale of its experimental practices. The usual markers of “big science” are multimillion dollar investments from governments, corporations or private foundations, the construction of dedicated facilities and equipment rather than the use of pre-existing, generic laboratory space, and complex, hierarchical staffing arrangements that, in addition to employing administrative and technical support personnel, coalesce sizable teams of researchers from across institutions, disciplines and, increasingly, national boundaries.[[1]](#footnote-1) Against such criteria, the claim of cosmology to the status of a ‘big science’ is relatively recent. Although the field now has access to an expensive assortment of ground-based and space-borne instruments – including CERN’s Large Hadron Collider, the Hubble Space Telescope, the Atacama Large Millimeter/Submillimeter Array and the Laser Interferometer Gravitational-Wave Observatory – which have afforded a remarkable power of sight into both macrocosmic processes and the elementary particles that set the parameters for cosmic history, it was not ever thus.[[2]](#footnote-2) For the early Cold War period, historians have tended to look elsewhere – to high-energy physics, quantum electronics, and upper-atmosphere research – to trace the effects of government largesse, organizational consolidation and condensing collective norms on the development of scientific practice and the production of scientific ideas.[[3]](#footnote-3)

Where the expansion of these other fields has been, rather grandly, implicated in geopolitical competition and large-scale socio-economic change, post-war cosmology is usually presented as advancing haltingly along its own narrow epistemic track until 1965, when – without evident cue or context – things suddenly changed. In the 1950s, cosmological research was not held in high esteem within either of its parent disciplines, physics or astronomy. The excitement stimulated decades before by Einstein’s theory of general relativity, which conceived of the entire universe as woven into a four-dimensional fabric of space-time and recast gravity as the warping of that fabric by energy and mass, had dissipated.[[4]](#footnote-4) In the United States, physicists seemed largely indifferent to the vaulting cosmos and its strange geometric kinks, instead driving downwards towards the sub-atomic frontier; that was where federal funds were flowing freely and new discoveries were being made - pions, neutrinos, heavy baryons.[[5]](#footnote-5) As the decade progressed, reflecting broader patterns of international scientific exchange, the scatter of European researchers conducting work on general relativity and gravitation began to condense into a community, whilst an infant network of American physicists made efforts to end the long estrangement between the quantum and relativistic scales of concern.[[6]](#footnote-6) The Princeton physicist John Wheeler, who created the network, had become captivated by the question of what would be left of a massive star once it had exhausted its supply of nuclear fuel and experienced a gravitational collapse, an enquiry that would, in time, help produce the modern concept of the black hole.[[7]](#footnote-7) Meanwhile, Wheeler’s colleague, Robert Dicke, established a research group devoted to empirical gravitation studies and embarked on a series of experiments to test Einstein’s model whilst also developing his own alternative cosmological theory, which proposed that the gravitational constant assumed by both Newton and Einstein might actually be affected by the distribution of mass in the universe.[[8]](#footnote-8) But confidence in the promise of cosmology as an intellectual field did not extend widely beyond the Princeton campus, nor did it run very deep. Few other physics departments in the United States encouraged their graduate students to undertake coursework in general relativity.[[9]](#footnote-9) Dicke himself observed that external agencies, having received his applications for funding to support his group’s experimental program, could find it “very difficult if not impossible to obtain an informed, sound, outside judgment” on the scientific value of its work.[[10]](#footnote-10) In 1966, an official report on “the present state of US physics and its requirements for future growth,” offered no prescriptions for capacity-building in cosmological research – in contrast to the directness of its recommendation that annual federal funding for particle physics be more than doubled.[[11]](#footnote-11)

Cosmology transformed: the significance of the cosmic microwave background

The purpose of this article is to re-examine and redefine the circumstances that encouraged the physical sciences, across a broad front of institutions, to re-invest in the study of time and space on cosmological scales. According to most historical accounts, the principal catalyst for the revival of cosmology as a research field was the detection of what became known as the cosmic microwave background (CMB) – a faint, almost uniform radiation saturating space in all directions at a temperature of around 3oK, just above absolute zero - and the identification of that radiation as the relict heat of ‘big-bang’ nucleosynthesis, now much cooled due to the expansion of the universe. The discovery of the CMB, announced to the world in 1965, seemed to confirm that the universe had a story – its past was very different to its present, its future might be very different still – and that formative stages in that story were now accessible to observation and experiment. But if the revival of cosmological science was a consequence of the discovery, what factors and contexts – antecedent to that revival - explain the discovery itself? To the extent that the existing literature presents an answer to that question, it has tended to prioritize the fortuitous concourse of highly localized expertise in cosmological theory, available in the form of Dicke and his group at Princeton, and the blind action of chance, which dropped empirical evidence consistent with the existence of a microwave background into Dicke’s lap just at the point that his group were starting to look for it themselves.

This article offers a different perspective. Against the reading of cosmology in the 1960s as a diffuse, ruminant and unworldly intellectual field suddenly restored to vigor and significance through the workings of happenstance, it identifies the discovery of the CMB as an exemplary product of Cold War technoscience: the cosmological research undertaken by Dicke’s group at Princeton was made possible by financial support from the American government, including the US armed services; meanwhile, the actual detection of the CMB occurred as a result of advances in microwave radio communication techniques which had attracted wide interest and investment across the military-industrial complex; and it was facility with such techniques as much as mastery of cosmological theory that underpinned the attribution of the 3oK radiation measurement to the early universe. The article affirms but also amplifies the insight offered by Benjamin Wilson and David Kaiser in their account of how MIT’s Lincoln Laboratory, in much the same period, and using technologies designed for the very different purposes of missile tracking and space communications, came to conduct a test of Einstein’s prediction that gravity slows down light: cosmology did not subsist in an academic sanctuary apart, at a remove from terrestrial politics and the grand technological capacity-building projects of the American national security state.[[12]](#footnote-12) The study of the cosmic whole as it extended across time and space was deeply implicated, just like other scientific fields, in the Cold War here and now.

Cosmology’s reputation within the physical sciences had long been afflicted by its failure to produce a definitive answer to the question that seemed logically to precede all others: did the universe have a beginning? In the late 1920s, Belgian Georges Lemaître had shown that an expanding universe satisfied the principal terms of relativistic mathematics and Edwin Hubble had correlated the most reliable measurements of distances to other galaxies and the velocities at which those galaxies were moving away, confirming that the most distant galaxies were travelling away most quickly.[[13]](#footnote-13) A number of key cosmological authorities, including Einstein, moved to endorse Lemaître’s evolutionary model.[[14]](#footnote-14) However, Lemaître’s subsequent proposition - that in its initial state, prior to its expansion, the entire universe had been contained within what he called a “primeval atom” – could not claim the same observational support.[[15]](#footnote-15) It was only in the late 1940s that the physical processes that would have immediately followed the expansion of the universe from a highly-compressed “primeval” state started to be plotted systematically. George Gamow, Ralph Alpher and Robert Herman demonstrated that chains of neutron-capture reactions in the dense superheated conditions of an early universe could have synthesized the elements of hydrogen and helium in the abundances found in the chemistry of the present-day cosmos.[[16]](#footnote-16) Over the next few years, Alpher and Herman went on to develop a comprehensive, richly-theorized account of the physics that would have been at work in the first ten minutes after any expansion began.[[17]](#footnote-17)

However, many scientific experts were unpersuaded that the puzzle of how the universe had come into being had now been solved. Some were vexed philosophically by the proposition that the physical laws of the universe had been produced by an expansion out of a singular, inscrutable condition to which those laws did not apply. But sceptics could also point to a long-standing discrepancy between estimates of the time that had passed since the start of the expansion - estimates derived from Hubble’s measurements of galactic distances and recessional velocities - and radiometric evidence of the age of the earth.[[18]](#footnote-18) By the early 1950s, the earth was known to have existed for at least three billion years; in 1953, new research added another one and a half billion years to that count.[[19]](#footnote-19) Hubble time, in contrast, stood at 1.8 billion years, apparently making the universe younger than its constituent parts.[[20]](#footnote-20) From these two reservations – one philosophical, the other empirical – emerged an alternative cosmological theory which reasoned that the fact of expansion did not rule out an eternal universe, assuming that sufficient matter was continually created within that universe to equilibrate its mass density and maintain it in a homogenous “steady state”.[[21]](#footnote-21)

Not everyone who considered the case for a finite-age universe to be unproven went on to endorse its rival, for the “steady-state” model was itself hardly innocent of speculative physics. Moreover, as the decade wore on, new observations using the 200-inch telescope on Mount Palomar – a long-delayed legacy of interwar “big-science” cosmology, which had finally entered operation in 1948 - required estimates of the size and therefore the age of the universe to be revised upwards from their previous values, from 1.8 billion years to a figure in the range of 6.6-13.3 billion, removing the timescale difficulty for those who traced the process of expansion back to a primordial “big bang”.[[22]](#footnote-22) The surveys of extragalactic sources of radio waves being conducted across the rapidly developing field of radio astronomy, meanwhile, revealed a distribution – an excess of faint, far-away sources - that was hard to reconcile with “steady-state” cosmology, which predicted that matter would be scattered evenly throughout the universe.[[23]](#footnote-23) Quasars, a class of prodigiously powerful radio objects first identified in 1963, all abided like feral exiles in the outermost regions of observable space.[[24]](#footnote-24) By the early 1960s, those astronomers who reflected on the cosmological implications of the data being generated in their field tended to conclude that, though such data was often provisional, ambiguous and highly contingent, it had – on balance - made the description of the universe offered by “steady-state” theory rather less plausible.[[25]](#footnote-25) But the alternative “big-bang” model had itself not advanced much beyond the conjectures developed a decade before: the signals recently received from remote radio objects were not obviously convertible into a conclusive proof-test of cosmological nucleosynthesis.[[26]](#footnote-26) By the late 1950s, the pioneers of “big-bang” physics - Gamow, Alpher and Herman – had all migrated to other research fields, and their papers on the subject, to judge by citation indices, now subsisted in a twilight of disciplinary indifference.[[27]](#footnote-27) The intellectual priorities of most American physicists in this period, as Steven Weinberg later recalled, lay elsewhere: “the study of the early universe was widely regarded as not the sort of thing to which a respectable scientist would devote his time.”[[28]](#footnote-28)

The discovery of the CMB, announced in 1965, and its detection at wavelengths across the microwave spectrum over the next two years, decisively ended the stalemate. The saturation of the heavens with background radiation was more consistent with models of a universe, superheated at birth, expanding outwards than with theories of a “steady-state” cosmos, infinite in age, in which such radiation would be an orphan, lacking any obvious physical source. Other developments in astrophysics in the mid-sixties – the ongoing work on quasars, the discovery of neutron stars, and the elaboration of general relativity to describe the properties of black holes – also served to revive interest in the broader constitution of the cosmos, for they revealed that the serene celestial canopy was no less convulsed by radical violence than the pretty blue planet it enclosed.[[29]](#footnote-29) But efforts to account for such prodigious phenomena, and to explain more generally the formation of large-scale structures in the universe like stars and galaxies, increasingly integrated the assumption that the process of cosmic expansion had its origins in a hot “big bang”.[[30]](#footnote-30) In recent decades, a number of fine-grained surveys of the CMB have been conducted, with scientists regarding it as an invaluable physical archive for the testing and refinement of cosmological ideas, including the theory that the universe “inflated” at an exponential rate in the first nanosecond of its history, Einstein’s prediction that the movement of masses produces gravitational waves, and conjectures about dark matter and dark energy.[[31]](#footnote-31)

By the late 1970s, then, it was clear that the confirmation of the “big bang” theory had contributed to the revival of cosmology as a scientific field, as reflected in year-on-year increases in the number of doctoral dissertations completed and journal articles published on cosmological themes, the introduction of cosmological modules into the curricula of university physics departments, and the commissioning of new textbooks by academic presses.[[32]](#footnote-32) Publishers also discerned a demand for works which explained “big-bang” cosmology in terms accessible to a general readership.[[33]](#footnote-33) It was in this context of a rekindled scientific and popular curiosity about the universe at large that astronomers and physicists were able to both conceive of useful cosmological research projects on the multimillion dollar scale of “big science” and believe, sometimes correctly, that those projects would attract the public support that was essential if they were actually to be funded and brought to fruition.[[34]](#footnote-34)

Ascribing discovery to serendipity: the case of the CMB

Accounts of the discovery of the CMB, written by journalists and other popular science authors, can be found in any library worthy of the name.[[35]](#footnote-35) Within the world of science, participants, bystanders and those whose own careers in cosmological research were enabled by the discovery have also pilgrimed back to the mid-1960s to tell the tale anew, apportioning credit, identifying lessons.[[36]](#footnote-36) Studies by academic historians, however, remain few in number, and none have yet ventured very far into the available archival record.[[37]](#footnote-37) In distinction to existing accounts, this article draws from an array of archival sources, contemporary scientific and technical publications, and participant recollections, in order to define more clearly both the material conditions and the modes of expertise that led most directly to detection of the radiation and its identification as a remnant of a hot early universe. In particular, it asks whether mastery of cosmological theory should be regarded as the primary standard for judging whether those involved in the discovery actually knew what they were doing: the predictions derived from such theories were not always precise, reducing the prospects for successful experiment. It also suggests that the contributions made to the discovery by researchers then working outside the field of cosmology should not be simply conflated with the action of chance: their accumulated skills and resources had left them better placed than anyone else to detect the radiation and register it as anomalous, even if they did not connect it to the origins of the universe. In its emphasis upon the material circumstances of scientific enquiry, the development of technical expertise and the permeability of disciplinary boundaries, the article situates the discovery of the CMB in the sort of explanatory context more familiar from histories of Cold War nuclear and electronics research, where funds flowed freely across a broad front of institutions and subject fields, underwriting innovation and exchange, and incentivizing the instrumentalization of basic knowledge to address real world problems: in this case, microwave radio noise. It was not research to resolve the “big-bang”/“steady-state” controversy that pulled the radiation within range of detection, but a protean technoscientific program to improve signal-to-noise ratios.

That the universe was still bathed in a radiation remnant from the process of cosmological nucleosynthesis had been predicted in the models developed by Alpher and Herman in the late 1940s; they had also estimated its present-day temperature to be around 5oK.[[38]](#footnote-38) But those predictions had no discernible influence on the research that led to the actual discovery of the CMB fifteen years later. During the 1970s, as the significance of the radiation to the reputation of the ‘big-bang’ model and to scholarly production within the broader cosmological field became more obvious, Alpher and Herman insisted that they had also made assiduous efforts to consummate their theoretical computations through astronomical observation. They told the physicist Steven Weinberg, who was writing *The First Three Minutes*, a book on “big-bang” cosmology intended for the general reader, that they had in the 1950s approached at least three institutions with radio astronomy programs to explore the possibility of detecting the radiation, but “were given to understand” that the signal from such a low temperature phenomenon could not be isolated from other sources of noise.[[39]](#footnote-39) However, this was a recovered memory, to be regarded – like all recovered memories – with a measure of circumspection. Not many years before, their recollections had been different. In 1967, Alpher had noted that he and Herman, having produced their prediction, gave “very little thought to the question of detection,” because “microwave radio astronomy was pretty much in its infancy.”[[40]](#footnote-40) In correspondence the following year, he recalled their assumption at the time that the background radiation could not be distinguished from the thermal energy emitted by stars, “and so we did not pursue the question of observation.”[[41]](#footnote-41) Whatever the reason – incuriosity or error - their prediction was never incorporated into an astronomical program; it was consigned like the rest of their work to the dusty, untrodden limbo of library periodical stacks.

The CMB, therefore, was left to journey towards the center of astrophysical enquiry via a much more circuitous route. Famously, in 1964, it was picked up in a horn-shaped antenna being used by two young radio astronomers, Arno Penzias and Robert Wilson, working for Bell Telephone Laboratories (Bell Labs), the research arm of AT&T. The radiation took the form of a persistent static noise, equivalent to a temperature of 3.4oK, crackling through the instrument regardless of where it was pointed in the sky. Penzias and Wilson, who were unaware of Alpher and Herman’s work predicting the existence of a microwave background, did not view their reading as a clue to the origin of the universe. It was instead a confounding impediment to their planned program of research. They had been calibrating the antenna with the intention of measuring the faint halo of radiation around the Milky Way and ascertaining whether matter in the form of hydrogen diffused into the vacuum of inter-galactic space.[[42]](#footnote-42) These were observations to be conducted in the lowest possible temperature range – just above absolute zero – where precise readings of differences of a few degrees were critical to the significance and credibility of the results. Unless Penzias and Wilson could account for all the noise in their antenna, their measurements would not stand.

Having worried at the mystery of this foundling noise for almost a year without resolution, Penzias and Wilson finally learnt of its possible connection to the primordial universe in early 1965 when they received word of a paper recently delivered at Johns Hopkins University by James Peebles, a post-doctoral researcher in the Physics Department at Princeton.[[43]](#footnote-43) Peebles had described his participation in the on-going effort of a small group of Princeton physicists, led by Robert Dicke, to test Dicke’s theory of an oscillating cosmos, one that expanded and then collapsed, expanded and collapsed, in an endless regenerating cycle. Dicke’s interest in evolutionary cosmology had been kindled by his broader attempt to contest general relativity, because - according to his alternative model – gravity was not a constant: it would have been a more powerful force when the universe was young.[[44]](#footnote-44) In summer 1964, he had proposed that, at the end of each oscillation, in the bounce between cosmic death and rebirth, an intense “fireball” was required to burn away the heavy elements that had been formed during the life of the previous universe.[[45]](#footnote-45) If his theory was correct, Dicke observed, a faint afterglow from the original inferno would have persisted into the present in the form of microwave radiation.[[46]](#footnote-46) Peebles had taken on the task of modelling the processes involved in order to calculate the likely current-day temperature of that radiation; two other colleagues, David Wilkinson and Peter Roll, were building an antenna with which to detect it.[[47]](#footnote-47)

Dicke’s ideas about the incineration of all but the lightest elements in a phase of cosmic collapse were incongruent with the elaborate account of matter creation in a hot “big bang” provided in the work of Gamow, Alpher and Herman a decade before. They had also been developed in apparent ignorance of that account. Dicke remembered attending a talk that Gamow had given at Princeton, presumably early in the formation of the “big bang” model, describing a primordial process of nucleosynthesis in which heat did not play a role; he claimed it had escaped his attention that temperature had subsequently become intrinsic to the theory.[[48]](#footnote-48) Peebles himself, who was more intrigued by the history of heat in the present universe than he was invested in Dicke’s meta-cosmological speculations, had read a paper written by Alpher and Herman on the origin of the elements, but he had not – at this stage – come across the articles in which they had extrapolated their model to derive estimates of the temperature of the surviving radiation background.[[49]](#footnote-49) Peebles was continuing to refine his own calculations and Wilkinson and Roll were still assembling their antenna when, in the middle of a group meeting to assess their progress, Dicke received a call from Arno Penzias.[[50]](#footnote-50) Might the studies being conducted at Princeton, Penzias asked, have something to do with the noise that kept soughing through the Bell Labs horn? Putting down the telephone at the end of the conversation, Dicke commented: “Boys, we’ve been scooped.”[[51]](#footnote-51)

The CMB, therefore, did not arrive at the threshold of scientific discovery having been carried, in textbook fashion, along a linear route that began with the initial development of a theory and the derivation of a prediction from it, through the design of an experiment to test the prediction, to eventual observational confirmation. Inaction, indirection and inadvertence all shaped its strange career. The scrimmaging between proponents of the “big bang” theory and those who favored the steady-state alternative ground on, but at a distance: none of those involved in the detection and identification of the radiation had very much staked on its outcome. Indeed, if the vitality and coherence of cosmology as a scientific field had been construed at that moment from the surface circumstances of the discovery, it is likely that the diagnosis would have been adverse. Researchers were unevenly lettered in the field’s foundational texts; their networks were loose, operating only fitfully; and the empirical approaches they employed seemed to be governed more by local preference than by any collective view as to which were the most likely to yield major advances in knowledge. In turn, it is no surprise that accounts of the discovery of the CMB, framed against such an unpropitious context, attribute it in large measure to the action of chance.

On 21 May 1965, in a front-page report announcing the discovery and outlining its potential to transform cosmological debate, the *New York Times* noted that the accidental conjunction of the Bell Labs antenna readings and the predictions produced at Princeton “may prove to be one of the most remarkable coincidences in scientific history”.[[52]](#footnote-52) The article, written by science editor Walter Sullivan, also compared the detection of the CMB to the first revelation, back in 1933, that radio waves travelled through the universe just as readily as light, a revelation resulting from Karl Jansky’s detection of powerful radio emissions from the centre of the Milky Way. Both observations, Sullivan pointed out, had occurred as serendipitous by-products of studies directed to different goals: in Jansky’s case, identifying the sources of static in short-wave transatlantic radio transmissions. In the same report that introduced the world to the physical phenomenon of the CMB, therefore, the *Times* inaugurated the practice of defining the radiation’s discovery as fortuitous. In 1978, the year in which the Nobel Committee for Physics marked the significance of the measurements made by Penzias and Wilson by awarding them its annual prize, the physicist Philip Morrison narrated a PBS television documentary about the CMB in which he described their work, and its “mix of chance and care,” as “the lucky start toward today’s cosmology”.[[53]](#footnote-53) For their part, Penzias and Wilson needed no highly sensitive antenna to detect, under the applause that accompanied their receipt of the Nobel Prize, a bass note of murmured depreciation. Penzias was aware that they were regarded in some quarters as “two telephone engineers” for whom the CMB had been just garden-variety radio interference before a team of proper scientists intervened to explain to them what they had found.[[54]](#footnote-54) In their twin addresses at the Nobel ceremony, Penzias and Wilson made a conscious effort to demonstrate a confident command of cosmological science, to establish the broader significance of the astronomical research program that they were pursuing at the time of their excess measurement, to show how dependent that measurement had been upon their combined instrumental talents, and to document their commitment to discovering its cause.[[55]](#footnote-55) Penzias, preparing his address, talked at length to Alpher to learn more about the early history of the “big bang” model. Alpher later claimed to have given him “a crash course on cosmology, and he didn’t know a damned thing.”[[56]](#footnote-56)

For Helge Kragh, it was indeed “somewhat surprising” that the Nobel Prize went to Penzias and Wilson.[[57]](#footnote-57) That the *New York Times* had splashed their measurements of excess temperature across its front page was due to the connection drawn by Dicke and his colleagues between that excess and theories of cosmic history, while Alpher and Herman could reasonably believe that confirmation of the correctness of the “big bang” model was an achievement of lesser note than development of the model itself.[[58]](#footnote-58) Kragh, as we have seen, is hardly alone in regarding the discovery of the CMB as “serendipitous,” but the implication that Penzias and Wilson had not really earned their good luck registers more strongly in an account of the “big-bang”/“steady-state” controversy which accords “high priority” to the agency of ideas.[[59]](#footnote-59) Credit for a discovery, Kragh suggests, requires more than the act of observation; the observations must have been prompted by theory or, alternatively, served as a prompt to the observers to identify a theoretical explanation for what they had found.

For their part, radio astronomers have often assigned the detection of the CMB to a long catalogue of serendipitous discoveries occurring in their field, beginning with Jansky’s detection of noise emissions from the galactic core. The first generation of radio astronomers, narrating their early adventures, cheerfully recounted story after story of significant phenomena detected by chance. By means of such tales, they established a claim to disciplinary distinctiveness. Radio astronomy was being presented as a field that had condensed from the labor of scientific outliers, who struggled to secure a home amongst either physicists or optical astronomers, who had to reach far and wide, frequently beyond national borders, to identify interlocutors or collaborators, who lacked – at least initially – large-scale federal funding and dedicated research facilities, who therefore became adept at building their own equipment and optimizing its performance, and who continued to be invested in an ethic of scientific autonomy that, across other better-resourced realms of post-war research where outcomes tended to be programmed in advance, appeared increasingly anachronistic.[[60]](#footnote-60) To radio astronomers, serendipitous discoveries had been common in their field because they had chosen to keep their channels open and remain alert to the anomalous signal, and not to screen that signal out as extraneous to their project goals. What received much less emphasis within the memory of these early practitioners, however, was the manner in which their routines of commerce with the wider military-industrial research economy started to quicken and thicken almost as soon as radio astronomy had become constituted as a distinct scientific field.[[61]](#footnote-61) Very few practitioner reminiscences reflected on how Cold War geopolitics may have substantially changed the odds of discovering something new.[[62]](#footnote-62)

As our philosophers and sports writers tell us, there are many different ways to think about luck. Circumstances are often plastic to re-framings that make the events that occurred within them more probable, or less; similarly, experience and expertise, depending on the angle from which they are viewed, may afford human actors substantial control over those events, or very little. In the context of particular stadiums, pitchers and field settings, and in the light of certain statistics on batter performance, the individual base hit - or even home run – may look less like a lucky break than it does a consequence of ability well-matched to conditions.[[63]](#footnote-63) Arno Penzias himself conceived of serendipity in terms of a commonplace saying that he (erroneously) credited to the baseball executive Branch Rickey: “luck occurs when opportunity meets preparation.”[[64]](#footnote-64) The relationships between luck and skill, and luck and circumstance, have been extensively debated, with the competing arguments extrapolated as far as they will go: everything is luck, including the fact that the universe exists; everything that happens is probabilistically determined by what has happened before, so luck does not exist. In the wide middle ground between those two positions, human agency – in our case, scientific accomplishment – is still possible, but giving measure to it depends on proper appreciation of governing contexts. If the sites of cosmological expertise existing in the United States in the early 1960s were plotted on a map along with major centers of microwave research and indications of funding flows towards each from government and industry, then the discovery of the CMB might start to seem like a rather normative outcome of Cold War-era investments in fundamental and applied science, with the accumulation of proficiency in microwave communications at Bell Labs no less significant to the breakthrough than Princeton’s institutional genius for theoretical astrophysics.

*Cosmology as Cold War science*

In the immediate post-war period, there was sustained debate within the sciences, the social sciences and the broader public sphere about whether scientific progress would be better achieved through deliberate, well-defined programmatic studies implemented in anticipation of specific instrumental returns or by cultivating research into fundamental problems.[[65]](#footnote-65) The results of any particular investigation into the basic properties of nature and matter ‘cannot be predicted with accuracy,’ observed Vannevar Bush, director of the wartime Office of Scientific Research and Development, in 1945. Nevertheless, he said, ‘Basic research leads to new knowledge. It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn. New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science.’[[66]](#footnote-66) It was this assumption – that basic scientific research, by constantly refreshing society’s creative sectors with ever-sharper, sometimes serendipitously-acquired, insights into the physical world, was the primary driver of national intellectual and material advance – which eventually extended the catchment for federal research support to include cosmology, one of the ‘purest realms of science’.

Bush was arguing for the continuation – indeed, the expansion – of government investment in basic science once the conflict was over. Broadly speaking, he got what he wanted, though the funding received by laboratories in the post-war era percolated down through an institutional ecology more imprinted by military interests and susceptible to change than he would have considered ideal. Levels of state support for basic research in the physical sciences were frequently affected by external events. A brief summer of liberal provision in the late 1940s ended with the outbreak of the Korean War, which prompted the principal funding agencies – the Atomic Energy Commission and the Office of Naval Research – to prioritize research programs likely to lead directly to defense applications.[[67]](#footnote-67) Even after the 1953 armistice, official trust in the invisible hand that conjured useful knowledge from the underwriting of free scientific enquiry continued to be brittle, thinned out by both President Eisenhower’s preoccupation with budgetary restraint and the flinty instrumentalism of Secretary of Defense Charles Wilson, for whom basic research was what scientists claimed to be engaged in “when you don’t know what you are doing.”[[68]](#footnote-68) It took the Sputnik crisis of 1957 to crystallize a new consensus, endorsed eventually even by Eisenhower himself: that the Pentagon’s short-term, utilitarian approach to subsidizing research had to be abandoned if the American failure to be first into orbit was not to presage broader degradation of the nation’s ability to push forward the frontiers of science and stimulate new revolutions in technology.[[69]](#footnote-69) After Sputnik, the ONR increased its support for research programs directed towards the advance of fundamental knowledge, whilst the National Science Foundation, which had subsisted on lenten fare since its creation in 1951, was now lavished with appropriations.[[70]](#footnote-70)

One of the beneficiaries of the crisis was Robert Dicke at Princeton. In July 1958, his group of gravitation researchers was awarded a contract with the ONR, receiving a total of $184,797 over the next four years.[[71]](#footnote-71) In November 1961, Dicke also successfully applied for a recurrent grant from the NSF.[[72]](#footnote-72) Between July 1962 and June 1964, the group received $210,000 in NSF funding, alongside an annual sum of $58,000 from the ONR.[[73]](#footnote-73) These contracts included provision for graduate support: in 1964-65, around ten graduate students were associated with the group, in addition to six members of staff.[[74]](#footnote-74) That same year, the contracts also contributed substantially to the salary costs of Dicke’s colleagues Peter Roll and James Peebles, with David Wilkinson lined up to receive ONR support after July 1965 when Roll would move on to a position elsewhere.[[75]](#footnote-75) The group perceived itself to be deprived only with respect to equipment funding, Dicke informing the ONR that “we are continually forced to make apparatus that could be bought and to beg and borrow where we can.”[[76]](#footnote-76) The bite of austerity, however, refreshed the group’s perception of its own independence. The need to adopt an artisanal approach to experimental design was not obviously more oppressive than the accounting procedures that would have accompanied a fully costed grant. In his annual reports to the ONR, Dicke was expected to identify what the gravitation group had accomplished over the previous year and to present a one-page budget outlining its financial requirements for the following period.[[77]](#footnote-77) Although the agency sometimes turned down Dicke’s requests for a funding increase, it did not try to influence the direction of the group’s research.[[78]](#footnote-78) Dicke himself observed that ONR support involved “a minimum of formal contractual troubles”.[[79]](#footnote-79) The gravitational effects that he and his colleagues sought to discern – to determine whether the universe was arranged in accordance with Einstein’s general theory or Dicke’s alternative model - were far too subtle on a local scale to invite any anticipation of strategic applications on the part of his sponsors. By the early 1960s, then, the Cold War state, entangled though it was in its own earthly emergencies, had assumed the role of benevolent patron for a research program to elucidate the invisible geometry of the cosmos-at-large.

Radio astronomy and the trading zone in microwave research

In many other post-war laboratory settings, however, it was often difficult – even after Sputnik - to tell the difference between research programs directed towards an instrumental goal and those focused on basic science. Both could involve the exploration and manipulation of fundamental physics. Whether it was inked into the budget of a government research facility, a military contract awarded to a university department, or the operational philosophy of a corporate laboratory, support for non-applied research was rarely entirely innocent of aspirations for an instrumental pay-off further down the line. If cosmology as Robert Dicke was able to practice it in the early 1960s represented something close to an ideal type, the field of radio astronomy - and its first-generation graduate researchers like Penzias and Wilson – came to maturity already scuffed by experience and implicated in a complex world. The paths that Penzias and Wilson followed through their doctoral studies and into professional employment had been charted and cleared only recently by military and industrial interests prospecting the frontiers of microwave radio technology. It was the funding channeled by such institutions into microwave radio research, stimulating innovation in instruments and techniques, that made possible one of the most important fundamental astronomical discoveries of the post-war era: the detection of the CMB, the first light of the universe.

Despite a national advantage conferred by the precedents set by Jansky and a wide reservoir of relevant expertise plenished in the course of wartime radar research, there were not many US scientists in the first post-war decade who identified themselves as radio astronomers, with the major innovations in the field occurring overseas, particularly in Australia and Britain.[[80]](#footnote-80) For most Americans seeking to make their careers in the physical sciences in the late 1940s and early 1950s, the real action lay in experimental encounters with the atom, which offered a near-term promise of strategic applications, not in eavesdropping on the noises emitted by distant stars. But the US military did come to take some fledgling interest in the field. The principal cluster of American radio astronomical expertise in this period could be found at the Naval Research Laboratory, which was also the site of an engineering program to detect the location of Soviet radar installations by capturing their signals as they reflected off the moon. Subsequently, during the Korean War, the NRL constructed the world’s largest parabolic antenna, carving it into the ground at Stump Neck, Maryland, precisely to harvest such stray feeds of electronic intelligence (ELINT).[[81]](#footnote-81) In 1954, looking to supersede Stump Neck with a 600-ft radio telescope to be built in West Virginia, the NRL invited its radio astronomers to participate in the initial design discussions. In return for a promise of access to the new telescope, the radio astronomers played a key role in public promotion of the project, directing attention away from its primary intelligence function, towards its potential value as a scientific instrument.[[82]](#footnote-82) Cost over-runs and the advent of ELINT satellites eventually caused the project to be cancelled, but its conditions of its nativity prefigured wider changes to come: with resources washing promiscuously through the institutions of post-war science in search of transformative technologies, radio astronomy could no longer expect simply to be left to its own devices.

Over recent decades, historians have unsealed and unbounded what was once regarded as the standard spatial unit of scientific practice – the laboratory - and diffused it into larger geographies, most notably that of the “trading zone”.[[83]](#footnote-83) Within such a zone, academic, government and corporate institutions may exchange information and resources, or work actively in concert, in order to accelerate progress on a specific set of scientific questions of significance to them all; different disciplines and categories of knowledge workers – theorists, experimenters, engineers - may also participate in the collaboration, loosening traditions, flattening hierarchies and blurring the distinction between basic and applied research. By the late 1950s, the common interest of US defense, telecommunications and scientific institutions in extending the useful range of the electromagnetic spectrum had helped to produce a trading zone in microwave research, connecting the diverse post-war fronts on which the properties and utilities of higher-frequency radio signals and radiation were being explored.

Within campus laboratories, the fields of atomic physics and physical chemistry were being revolutionized by the technique of microwave spectroscopy, which used high frequency beams to cause a shift in the quantum distribution of atoms and molecules, moving some from a low-energy to a high-energy state or vice versa and allowing researchers to probe more deeply into the elementary constitution of matter.[[84]](#footnote-84) For the military services, shifting communications systems into the microwave region was initially a means of remaining one step ahead of Soviet jamming technology. Once the Soviets had followed suit, developing their own microwave radar and communications capabilities, additional research was required to develop devices that, when installed on fighter and bomber aircraft, could jam such systems and not be jammed themselves, ensuring that the US deterrent could still be delivered.[[85]](#footnote-85) The advent of the satellite age, with its promise that reliable defense communication channels could be established across intercontinental distances at modest cost, further reinforced military interest in higher frequency radio; microwave signals would be used to relay messages from earth to satellite and back to earth again because, unlike longer wavelengths, they do not reflect off the ionosphere but instead travel through it.[[86]](#footnote-86)

After the end of the war, many civilian corporations – in the telephone, electronics and broadcast industries – also developed ambitious plans for a future of wireless communication, expecting microwave transmission to solve the perennial problem of a crowded frequency spectrum. Concerned to protect the investment made by AT&T in its landline network, however, regulators withheld permanent operating licenses from most of these enterprises, allowing the corporation to determine the pace of innovation in the field.[[87]](#footnote-87) By 1951, AT&T’s own meticulously engineered microwave radio relay system stretched from coast to coast.[[88]](#footnote-88) Throughout this period, Bell Labs’ radio researchers, based in Holmdel, New Jersey, worked to perfect the arts of microwave transmission and reception, whilst advancing basic knowledge of how such signals behaved when cast out into the world. In contrast to long-wave radio transmissions, which are most seriously affected by atmospheric static, microwave signals are susceptible to a broad range of lesser hazards. Ground radiation and local environmental noise, for example, could cause interference at the point of reception. The laboratory therefore experimented with a horn-shaped antenna design which, amongst other virtues, shielded the antenna beam more effectively than an open parabolic dish.[[89]](#footnote-89) Horn antennas were eventually installed on AT&T’s microwave relay towers across the country.[[90]](#footnote-90) Staff at Holmdel measured the attenuation of microwave transmissions as a result of water vapor and oxygen in the atmosphere.[[91]](#footnote-91) Funded in part through a contract with the US military, which was concerned to find ways of overriding Soviet radio jamming, they also explored the phenomenon of propagation beyond the horizon, testing the theory that microwave signals at low angles of elevation became trapped between reflective layers of the troposphere and the ground, bouncing like a tennis ball around the curvature of the earth.[[92]](#footnote-92) A number of these experiments were conducted from the top of Crawford Hill, a few miles from Holmdel. At the end of the war, Bell Labs had purchased a sizable parcel of land on the hill, which was the highest point along the mid-Atlantic coastal range, allowing line-of-sight transmissions to and from the main Bell Labs laboratory in Murray Hill, New Jersey.[[93]](#footnote-93) Between 1955 and 1958, antennas installed on the hill were used to test propagation of microwave signals transmitted along the same path from a site more distant than the horizon, 171 miles away in Pharsalia, New York.[[94]](#footnote-94) Swiftly thereafter, Bell Labs made an imaginative leap into space, conceiving of an experiment which would bounce microwave transmissions off a large metallic balloon orbiting above the earth in order to test the feasibility of transoceanic communication via satellite.[[95]](#footnote-95) Titled Project Echo, the experiment, conducted in collaboration with NASA, came to fruition in August 1960 when microwave signals sent from California, reflected by the balloon, were received by a large, purpose-built horn antenna at the Bell Labs ground station, which was sited atop Crawford Hill.[[96]](#footnote-96)

Radio astronomers arrived at an appreciation of the significance of the microwave spectrum in much the same way that, according to Hemingway, people go bankrupt: gradually, and then suddenly. Until the early 1950s, they were content to tune into the sky at lower frequencies, for there were always interesting objects disclosed by this method that optical astronomers could not see. One or two researchers did attempt to measure the microwave radiation emitted by the sun, but their readings did not attract wide interest.[[97]](#footnote-97) Then, in 1951, came news from Harvard: with a receiver set to a wavelength of 21 centimetres, physicist Edward Purcell and his student Harold Ewen had detected the spectral presence of low-temperature clouds of hydrogen in interstellar space.[[98]](#footnote-98) It was evident that radio astronomers had a new and important task ahead of them, beyond the study of discrete radio stars: using microwave techniques, they could draw a more detailed, deeply-layered map of the structure of the Milky Way. In the United States, federal agencies such as the ONR and the NSF now looked to build capacity in the field, and the major facilities that they funded – at the NRL in Washington, Caltech’s Owens Valley Radio Observatory, and the National Radio Astronomy Observatory at Green Bank, West Virginia – all made instrumental provision for research at shorter wavelengths.[[99]](#footnote-99) The particular value of the 21-centimetre wavelength for revealing invisible conformations of hydrogen - the most abundant element in the universe - was registered in the 1959 decision of the International Telecommunications Union to reserve that frequency exclusively for radio astronomical use.[[100]](#footnote-100) But the rapid assimilation of higher frequencies into the research practices of the field was also made possible by the ready availability, in laboratory stockrooms and second-hand electronics stores, of components left over from wartime experiments with microwave radar. Even those researchers subsidized by federal grants were apprenticed in the arts of forage, salvage and ad hoc equipment-making.[[101]](#footnote-101) As a graduate student at Caltech, Robert Wilson drove a caterpillar tractor to level and grade the ground for the Owens Valley Radio Observatory and thereafter built the electronics for its two microwave antenna receivers.[[102]](#footnote-102)

If any single institution lay at the centre of the trading zone in microwave research, linking deep experimental enquiries into the quantum states of matter with consultancy and contract work on military systems, innovation in communications, and, by the late 1950s, radio astronomical observations, it was Columbia Radiation Laboratory. And if there was any single individual at Columbia whose activities made manifest the broadening latitudes of the trading zone and the variety of transactions taking place across it, that individual was Charles Townes. An expert in microwave spectroscopy, Townes had moved to Columbia from Bell Labs in 1948. CRL was deeply entangled with the US military. Much of its funding came from the Army Signal Corps, the Air Force and the ONR under the Joint Services Electronics Program, which was intended to facilitate the continued advance of fundamental knowledge in this key, strategic field whilst also channelling research towards questions of potential relevance to military operations. In 1950, Townes was asked by the ONR to chair an Advisory Committee on Millimeter Wave Generation. It was a commission that motivated Townes himself, in collaboration with his graduate student James Gordon, to explore a new approach to producing higher frequencies, designing an apparatus which used a microwave beam to excite gas molecules contained within a cavity into a higher energy state and then fed the radiation they emitted back to those molecules to induce further emissions, generating an output of microwave radiation more powerful than the initial beam. As it turned out, the capacity of the device to generate microwaves drew less notice than the fact that it amplified the original signal: Townes accordingly named it the “Maser”, short for “Microwave Amplification by Stimulated Emission of Radiation”.[[103]](#footnote-103) Improving amplification of otherwise faint microwave signals promised to transform the performance parameters of a whole host of defense technologies, from radar and missile warning systems, intelligence listening posts and communications satellites.[[104]](#footnote-104) Townes’ achievement with the maser encouraged CRL to seek a substantial augmentation of its JSEP budget in order to develop more advanced versions of the device and investigate their potential applications.[[105]](#footnote-105) Meanwhile, laboratories elsewhere – in other universities, industry and government – initiated their own maser experiments, with the aim, in particular, of producing a solid-state model that could be tuned to a broader range of microwave frequencies.[[106]](#footnote-106) After completing his PhD, James Gordon was recruited by Bell Labs, which was looking to incorporate masers into its work on anti-missile systems.[[107]](#footnote-107) By 1958, as the maser was adopted as an integral component of the projected Echo satellite receiving system, Townes himself was consulting at Bell Labs for two days each month.[[108]](#footnote-108)

It was around this time that the networks of communication and collaboration created across a broad front of institutions and disciplines as a result of increasing use of microwave frequencies and the development of the maser widened conspicuously to admit radio astronomers. As they sought to map and measure the finespun clouds of hydrogen haunting interstellar space, researchers in the field were keenly interested in any innovations that would help them detect and amplify faint microwave signals without also amplifying noise internal to the receiver system. A device invented in the mid-1940s by Robert Dicke – the Dicke radiometer – had made it possible to measure the difference between the temperature of radiation registered in an antenna pointed at a particular external source and a reference load incorporated into the radiometer design; the device switched constantly from antenna to load and back again, allowing the spread of the two signals to be averaged out, converted into a single direct current and read on an output gauge.[[109]](#footnote-109) But that reading could not be translated into an absolute value for the external source itself without determining the contribution made to the antenna temperature by environmental noise and internal system components like the amplifier, and it was almost impossible to be precise in such determinations when the contributions themselves were large. Radio astronomers, then, joined the scrum of researchers looking to experiment with solid-state masers: not only would maser amplifiers markedly improve signal-to-noise ratios, they also had to be cryogenically cooled in order to work, sharply limiting their contribution to the overall temperature of the antenna system. The challenges that confronted radio astronomers as they tested and refined their masers, having constantly to draw each device in and out of its cryogenic bath, in the hope of achieving routine amplification of distant microwave signals had salience well beyond their own research field.[[110]](#footnote-110) Townes, who had already begun a collaboration with the NRL to install a solid-state maser on its 50-foot radio telescope, was encouraged by the Air Force in early 1959 to submit a proposal seeking funds to construct an antenna, complete with radiometer and maser, at CRL itself. He was told that applications to the service were most likely to be successful if they used “magic words”: on the list, alongside “microwave spectroscopy” and “masers,” was “radio astronomy”.[[111]](#footnote-111) The proposal, requesting $30,343, was submitted within a fortnight and swiftly approved.[[112]](#footnote-112)

Arno Penzias, Bell Labs and satellite communications

In 1958, Arno Penzias joined the large cohort of graduate students at CRL working under Townes’ supervision. He received around $200 a month from a half-time employment contract with the laboratory, funded out of its JSEP budget.[[113]](#footnote-113) For his doctoral thesis, Penzias elected to search for atomic hydrogen in galactic clusters, specifically in the spaces that separated their constituent galaxies; he had enough audacity to hope that his research might account for the “missing mass” within such clusters, a problem first identified by optical astronomers in the 1930s.[[114]](#footnote-114) It was an ambitious undertaking, and not only because – as we now know – hydrogen is a highly rarefied presence in the intergalactic medium, with an average density of only a few atoms per cubic metre. In order even to make his measurements, Penzias had to build the first tunable, solid-state maser amplifier to operate at a wavelength of 21 centimetres, a task that involved collaboration with Townes’ contacts at Airborne Instruments Laboratory, a Pentagon contractor which was looking to develop a similar maser for military use.[[115]](#footnote-115) Then he designed a receiver system in which he placed a reference load into the cryogenic bath alongside the maser, allowing him to accurately determine what portion of the antenna measurements were due to the noise outputs of the system itself.[[116]](#footnote-116) Penzias spent much of 1960 in Washington, DC, again supported from JSEP funds, constructing a mount so that his apparatus could be installed at the centre of a new disk antenna at the NRL; in particular, he had to devise a way to compensate for the tilt of the antenna so that the liquid coolant he was using did not spill.[[117]](#footnote-117) Finally, in the single month that the NRL had allotted him to make observations, he found next to nothing, certainly not nearly enough hydrogen to account for the ‘missing mass’.[[118]](#footnote-118)

This was not the sort of research result that would set the field aflame, but over the course of all the trials that he had experienced as he designed and conducted his experiment, Penzias had accumulated an unusual variety and depth of expertise with the tools – masers, cold reference loads, cryogenic liquids - that seemed likely to drive progress in microwave radio astronomy through the following decade. In 1962, there were only four observatories regularly using masers for radio astronomy; by 1966, that figure had risen to eleven.[[119]](#footnote-119) Moreover, Penzias’ skills were readily transferable to research fields which shared radio astronomy’s interest in improving signal-to-noise ratios. Since early 1959, when it had secured NASA’s agreement to participate in Project Echo, Bell Labs had been looking for a radio astronomer to join its staff.[[120]](#footnote-120) It wanted to do all it could to enhance reception of the signals to be bounced off the *Echo* satellite. The large horn-shaped antenna that it had constructed on top of Crawford Hill was combined with a maser amplifier cooled in a dewar of liquid helium, which was itself contained in an outer dewar of liquid nitrogen.[[121]](#footnote-121) As the receiver system operated almost continually throughout the day, large quantities of these cryogenic fluids had to be shuttled in twice a week from a Union Carbide facility in Tonawanda, New York; liquid helium had only just become commercially available.[[122]](#footnote-122) Bell Labs engineers had made meticulous attempts to identify and measure all contributions to antenna noise temperature from sources other than the incoming satellite signal. Oxygen and water vapour in the atmosphere were found to add an irreducible minimum of around 2.3oK to the antenna’s readings when its beam, in dry weather, was pointed directly upwards, along the shortest path through the sky; their noise contributions increased as the beam was lowered towards the horizon or as conditions became humid or wet.[[123]](#footnote-123) The engineers also calculated noise contributions from the antenna itself, its electrical components and the maser. Though the total measured system noise temperature was about 3oK higher than they had expected - 21oK rather than 18oK - the engineers assumed that there were small margins for errors in all their original calculations which explained the excess.[[124]](#footnote-124) The horn antenna was still an extraordinarily sensitive, low-noise instrument, well-matched to the task of space communications; enough was known about its properties, observed one Bell Labs technical essay in spring 1961, that the antenna could also be used “as a standard for absolute flux measurements in radio astronomy.”[[125]](#footnote-125)

It was around this time, just as he had completed his PhD final exams, that Penzias took up a position in the Bell Labs Radio Research Department, which had built the Project Echo receiver system on Crawford Hill. Townes had recommended him.[[126]](#footnote-126) If, in the mid-to-late fifties, CRL had been the institution where significant new adventures in microwave research were conceived, it was Bell Labs that was most likely to convert such research into applications that would transform peoples’ lives. For Bell scientists, communication was increasingly defined by the efficient transmission of information, not the transfer of meaning, a definition consistent with their work for the US military on missile guidance and high-speed systems to provide early warning of enemy missile attacks as well as their efforts to think beyond AT&T’s own existing core telecommunications infrastructure of coaxial cables, vacuum tube repeaters, electro-mechanical switches and dial telephone sets.[[127]](#footnote-127) In its attempt to advance to a futurity of seamless, limitless communication, encompassing microwave radio, communication satellites, electronic switching and the use of light to transmit voice signals and data, AT&T was prepared to invest substantially in basic research, albeit almost always in the hope of an instrumental pay-off further down the road. The applied and non-applied studies conducted by the Radio Research Department were central to the company’s ambition to network the world. Soon after the acquisition of the first signals from *Echo* by the Crawford Hill horn antenna, Bell Labs and AT&T accelerated their planning for an experiment with an active communication satellite, to be called *Telstar*, which would receive, amplify and relay a range of test transmissions sent from the ground, including television pictures with sound.[[128]](#footnote-128) The Radio Research Department was now the nucleus of a major strategic enterprise, which pulled in specialized expertise from all around Bell Labs: at its peak, 450 personnel were affiliated with the *Telstar* project.[[129]](#footnote-129)

For his part, Penzias had accepted the position in the department with a view to using the allowance in his contract for conducting basic research to repeat his thesis measurements, but he also quickly proved to his employer the utility of having an in-house radio astronomer.[[130]](#footnote-130) As the signals from *Telstar* would still be very weak by the time that they returned to earth, Bell Labs decided to construct a new, much larger horn antenna and to locate it not on Crawford Hill, but in a natural basin at Andover, Maine, a site better protected from terrestrial microwave systems operating on the radio frequencies to be used in the experiment.[[131]](#footnote-131) Within months of his appointment, Penzias had pointed out that bright radio stars could be used to calibrate the tracking system of the Andover horn so that its engineers would know precisely where in the sky it was pointing.[[132]](#footnote-132) Meanwhile, Bell Labs staff on Crawford Hill had been promised a new, massive antenna of their own, nearly identical to the horn at Andover, for the purposes of research.[[133]](#footnote-133) Penzias anticipated that the existing Crawford Hill antenna would soon be made available to him for radio astronomical work and that he eventually would have access to the massive horn too, once it was built. “I was telling everybody,” he recalled: “‘My god. I mean, it’s such a wonderful thing. Here they’re spending $5 million on an antenna and I’m going to be the only radio astronomer using it.’”[[134]](#footnote-134)

By late summer 1962, even as the recently launched *Telstar* satellite cycled overhead relaying live television images of the United States to Europe and vice versa, Penzias had been forced to downgrade those expectations. The French Ministry of Posts and Telecommunications, which was constructing its own facsimile of the Andover horn in Brittany to receive transmissions via *Telstar*, was unable to source all the materials it needed; components originally intended for the new Crawford Hill antenna were shipped instead to the French ground station to fill out its stocks.[[135]](#footnote-135) Moreover, the prospect that the French antenna would not be online by the time that *Telstar* was delivered into orbit prompted Bell Labs to call the *Echo* horn back into service as a satellite receiver, to provide a test of *Telstar*’s capacity to relay television signals from Andover on to a distal point.[[136]](#footnote-136) Penzias would not be converting the horn into a radio astronomical instrument any time soon.

Meanwhile, there were broader political currents blowing around Crawford Hill which had the potential to derange Bell Labs’ plans for the research to be conducted there after *Telstar*’s mission was completed. NASA had become concerned that AT&T, through *Telstar*, was endeavoring to establish its own complex, expensive technology as the standard for an American communication satellite (comsat) system, pre-empting the agency’s statutory responsibility for defining and directing the nation’s activities in space.[[137]](#footnote-137) Partly for that reason, NASA expressed a strong interest in an alternative system model developed by the Hughes Aircraft Company, which would provide global coverage through just three satellites placed in a stable, geosynchronous orbit. The direction of NASA’s preferences could be read in its award of a study contract to Hughes just prior to Telstar’s launch.[[138]](#footnote-138) In addition, ongoing controversies over AT&T’s use of predatory pricing to limit competition in terrestrial telecommunications markets kindled an apprehension that the company could not be trusted to operate a national comsat system in the common interest.[[139]](#footnote-139) A number of Democratic senators and congressmen warned the Kennedy administration that the system’s ownership structure should preclude any possibility of its dominance by AT&T.[[140]](#footnote-140) The administration responded by preparing a bill to create a regulated Communication Satellite Corporation in which telecommunications carriers would be restricted, in total, to owning fifty per cent of the shares; no single company could elect more than three candidates for the corporation’s fifteen-member board.[[141]](#footnote-141) Debated extensively in Congress through the middle months of 1962, the bill was eventually passed in late August. It was now unlikely, with AT&T’s leverage dismantled, that Telstar and the Andover horn antenna would be adopted as the hardware templates for the nation’s comsat system. AT&T started to scale back its investments in space communications research. There would be no massive horn built on Crawford Hill. Engineers there continued with satellite tracking and other experimental studies, but confidence in the scientific or business significance of such work was now ebbing away.[[142]](#footnote-142) “One can reasonably ask, why are we doing these things?,” one manager observed in May 1964.[[143]](#footnote-143) The same month, Bell Labs decided to close down satellite operations on the hill at the end of the year.[[144]](#footnote-144)

Measuring the CMB at Crawford Hill and Princeton

It was in late 1963, as Bell Labs slowly adjusted to the knowledge that innovation in space communications would take place elsewhere, that Penzias was finally given access to the *Echo* horn.[[145]](#footnote-145) By that time, Robert Wilson had joined him on the staff at Crawford Hill and, with the half-time allowance that each of them were afforded for conducting their own research, they worked together to adapt the instrument for radio astronomical use.[[146]](#footnote-146) As they were both interested in observing extremely faint phenomena – Wilson wanted to measure the weak halo of radiation around the Milky Way, Penzias wished to continue his search for inter-galactic hydrogen – they sought to reduce still further the noise internal to the antenna system and to establish accurate values for any noise sources that remained. In the first instance, they chose to continue working with the maser that had been installed on the antenna for the *Telstar* experiments. As the maser operated at the 7cm wavelength, rather than 21cm, it would not detect hydrogen, but it would enable them to confirm the low-noise properties of their equipment: pointed at the galactic peripheries, the antenna – deaf to the only radio source that they thought might be there – would produce a null reading. The complex labour of stripping out the 7cm maser and replacing it with one tuned to 21cm would be deferred until that test was done.[[147]](#footnote-147) In the meantime, Penzias sought to exploit another local legacy of the satellite work on Crawford Hill: the support staff there had become used to ordering large quantities of cryogenic liquids. He only had to ask for such liquids and “they brought them to you, just like they left the lights on.” This encouraged Penzias to build the best cold reference load he could imagine, because he knew that he would be able to keep it cold.[[148]](#footnote-148) For his part, Wilson, adept with electronics, designed a low-noise switch that allowed a comparison to be made instantly between the temperature of the antenna and that of the cold load, with the noise contribution from the maser and system electrics remaining constant across the two readings.[[149]](#footnote-149) In May 1964, the refit completed, he and Penzias directed the antenna towards a region of empty space, expecting the measurement to comprise 2.3oK of atmospheric noise as determined in earlier Bell Labs calibrations of the horn plus around 1oK of radiation from the walls of the antenna and ground, the sum of these sources being lower than the cold load temperature of 4.2oK. But just like the *Echo* engineers, they registered an excess: the reading was not 3.3oK, but 6.7oK.[[150]](#footnote-150) Over the next nine months, Penzias and Wilson worked through a list of conceivable sources for the 3.4oK excess, including man-made radio noise, galactic radiation, and leakage through the joints of the horn, ruling out each in turn.[[151]](#footnote-151) The mystery could not be attributed to any fault in their methods.

For six years, Crawford Hill had been the setting for a succession of careful antenna installations, upgrades, calibrations and measurements, culminating in the effort of Penzias and Wilson to fashion the *Echo* horn into an instrument capable of detecting the thinnest smears of radio matter extruding into inter-galactic space. Their skilful, scrupulous work convinced Dicke and his associates at Princeton that the source of the excess signal picked up in the horn was the remnant radiation from a hot early universe.[[152]](#footnote-152) It was difficult to see what else it might be. Shortly after Penzias’ telephone call, Dicke, Roll and Wilkinson travelled to Crawford Hill to meet with Penzias and Wilson and inspect their antenna: “they had good, sharp, crisp answers for everything we worried about,” Wilkinson recalled.[[153]](#footnote-153)

But the influence of observations conducted at Crawford Hill on the research program of the Princeton physicists was not confined to the bittersweet experience of having Dicke’s theory of a primeval fireball and its present-day residue confirmed by others before they could confirm it for themselves. Peebles had already consulted a Bell Labs report produced four years before which described an attempt to reduce internal system noise and determine the minimum contribution of atmospheric factors to antenna temperature. Peebles took the lowest antenna temperature value achieved in this study (18.5oK), subtracted atmospheric noise, and derived an upper limit for the cosmic microwave background of 15oK.[[154]](#footnote-154) In addition, having theorized values for the physical parameters that he regarded as most important to the thermal history of the universe – its rate of expansion, the changing ratio of neutrons to protons, the abundance of helium – Peebles had identified 10oK as the lower temperature limit.[[155]](#footnote-155) Prior to Penzias’ telephone intervention, then, the Princeton team had been assuming that the signal from the radiation would be rather stronger than it actually was. That the 3.4oK excess measured at Crawford Hill fell outside the range predicted in Peebles’ original model presented, Dicke acknowledged, “a problem” for that model.[[156]](#footnote-156)

It also clarified the instrumental challenge confronting Wilkinson and Roll. Neither had any real experience in the techniques of radio astronomy before they had embarked on the project of constructing an antenna - Wilkinson recalled that he ‘didn’t know anything about microwaves’ - so they had to train themselves on the job, combing the specialist literature for basic, practical information about the sort of equipment they would need.[[157]](#footnote-157) The most expensive items were beyond their budget. They roamed military surplus stores for second-hand electronic components, whilst trusting in Dicke’s gift for improvisation to compensate for other points of scarcity, such as the fact that they had no maser.[[158]](#footnote-158) The cold load was a particular challenge, having to be built from scratch and then immersed in a cryogenic bath.[[159]](#footnote-159) Then came word of the Bell Labs reading. Wilson subsequently suggested that it had forced the Princeton team to redesign their own apparatus to extend its observational range down towards absolute zero, though Dicke denied the claim.[[160]](#footnote-160) During a reciprocal visit that same spring, Penzias and Wilson viewed the apparatus that Wilkinson and Roll were assembling. Penzias, who could order whatever quantities of liquid helium he wanted, observed that the Princeton team’s greater economy with its use was likely to compromise the reference function of their cold load, increasing its temperature well beyond 4.2oK. He recalled: “I came away with the idea that if they had just done this with the equipment they had and hadn’t seen us they might have ended up with a null result the first time.”[[161]](#footnote-161) The cold load was eventually installed on the Princeton antenna in August. Its initial reference temperature of 10.66oK had been fine-tuned down to around 6.8oK by mid-October, allowing Wilkinson and Roll to make their own reliable measurements of the CMB at the 3cm wavelength over the following weeks.[[162]](#footnote-162)

Conclusion

In its concern with structure and direction in the universe, with encompassing the origins and future states of the cosmic whole, and its smallest and largest features, within common principles of causality, scientific cosmology is often presented, and presents itself, in the guise of a quest: the cosmologist, alone or in fellowship with others, purposefully sets out to find some specific facet of nature that will be difficult to find, that indeed might not exist, in the anticipation that success will make legible another layer of the natural order, bringing humanity one step closer to an understanding of it all.[[163]](#footnote-163) So it was, sure enough, with the research studies, long in duration, that led to the detection of the Higgs boson and gravitational waves.[[164]](#footnote-164) But the discovery of the CMB, which did more than anything else to revive cosmology as a research field, did not neatly conform to the typology of the quest. Penzias and Wilson were not searching for clues to the early history of the universe; the Princeton team were, but, for Dicke, their work was ancillary to his primary interest in challenging Einstein’s general theory, whilst his young associates, none of whom then self-identified as a cosmologist, had mostly committed to the project to broaden out their résumés.[[165]](#footnote-165) It is striking how lightly invested all these protagonists were in the on-going skirmishes between “big bang” loyalists and stalwarts of the “steady state”. Hence, perhaps, attributions of the discovery to the caprices of fortune in order to explain what intention cannot.

The unbounded scale of cosmology’s themes accounts for much of its allure as a field, but the remote and exacting environments – long underground tunnels, deserts, mountaintops and outer space - in which its grandest experiments take place endow it with additional prestige. The rigours of such environments attest to the discipline of the researchers involved. Yet, however separated their facilities may be from the usual settings of social exchange, however intensely they attend to the arrangement of the heavens, cosmologists continue to be, as monks of the middle ages were, citizens of the earthly world. Their funding, after all, does not fall from the skies or materialize in an instant out of proton collisions. As a tenured professor at Princeton, Dicke made his own decision to specialize in gravitation and cosmology, but the extension of that freedom to others at the university relied on grants from a federal government that, perturbed by Sputnik, sought to ensure national predominance in the scientific Cold War by supporting basic research across a wider horizon of subject fields. Penzias and Wilson, meanwhile, were serving their apprenticeships amidst the swelling conformations of American technoscience, where the commerce between technology-producing science and science-enabling technologies was broad and brisk, where the wash of national security interests and corporate ambitions, combined with the romance of working with newly-invented instruments, could have a shaping effect upon research activities that was at least as significant as the more customary routines of theory development and testing.[[166]](#footnote-166) In the late 1950s and early 1960s, radio astronomers seeking to perfect the art of observing low-noise celestial sources often shared laboratory accommodation and equipment with research programs directed towards enhancing military communication, missile detection or electronic intelligence, or commercial exploitation of the high ground of space. There would be many purposes advanced if microwave signals could be heard more clearly. The traffic of personnel, information and instruments across the trading zone in microwave research deposited a large horn antenna, maser and an ample supply of cryogenic liquids upon Crawford Hill, and carried Penzias and Wilson there as well. What Penzias and Wilson, with their accumulated hands-on expertise, assembled from such resources, was a world-leading interface with the radio universe, particularly its quietest regions.

“Were it not for the role of serendipity,” observed Robert Dicke after the award of the Nobel Prize to Penzias and Wilson, “it would have been Dave [Wilkinson] (with Peter Roll) who would have discovered the background radiation.”[[167]](#footnote-167) The Princeton physicists, as they edged their research towards its empirical phase, had a definite object in mind, but the contrast between their programmatic approach, integrating theory and observation, and Penzias and Wilson’s good luck becomes less vivid under close historical study. Before Dicke and his associates learnt of the measurements made on Crawford Hill, the theoretical model they had developed, neglectful of previous, more exact predictions, had been directing them towards the wrong temperature range; partly as a result, their antenna system, as originally designed, may have lacked the sensitivity to discern the CMB. Serendipity, moreover, is not totally indiscriminate in its dispensations of grace: it frequently bends providential, towards fields - like radio astronomy - in an early, open stage of formation, before the settling of intellectual agendas and methods of work, and towards researchers – like Penzias and Wilson - who have optimized the precision and power of their instruments.[[168]](#footnote-168) It was with purpose and care that Penzias and Wilson reconditioned their antenna and turned it to sound the depths of radio space; it was the same purpose and care which qualified the signal they picked up in those depths as something unusual and new.

ACKNOWLEDGEMENTS

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