IEEE Journal of Microwaves

Received 14 August 2020; revised 9 September 2020; accepted 14 September 2020.
Date of current version 7 January 2021.

Digital Object Identifier 10.1109/JMW.2020.3025246

Microwaves Are Everywhere
"CMB: Hiding in Plain Sight"

PETER H. SIEGEL [1,2,3] **(Life Fellow, IEEE)**

(Special Series Paper)

[1] THz Global, La Canada, CA 91011 USA
[2] Department of Electrical Engineering, California Institute of Technology, Pasadena, CA 91125 USA
[3] NASA Jet Propulsion Laboratory, Pasadena, CA 91109 USA (e-mail: phs@caltech.edu)

ABSTRACT This article is the first in a continuing series of general interest papers on the applications of microwaves in areas of science and technology that might not be evident to the casual observer. What better topic to start the series than an introduction to the most pervasive microwave field in the universe: the cosmic microwave background (CMB). The prediction, discovery, and importance of the CMB from a microwave engineering perspective are reviewed and discussed.

INDEX TERMS CMB, cosmic microwave background, microwave applications, microwave science.

I. INTRODUCTION

If one were to measure the spectral radiance (Watts per meter squared per steradian per hertz) versus wavelength in any arbitrary direction/location in interstellar or intergalactic space where there is no obvious source of localized energy (planet, star, dust cloud, galaxy, or any of the other more intriguing interstellar or galactic objects), the resulting plot would match that of a black body (perfect thermal emitter) obeying Planck's Law with a temperature of 2.72548 ± 0.0057 K [1], [2]: $B\,(f, T) = \frac{2hf^3}{c^2} \times \frac{1}{e^{hf/kT} - 1}$, where h is Planck's constant, k is Boltzmann's constant, c is the velocity of light, T is the temperature and f is the frequency. The peak of this energy emission plot occurs at a frequency of 160 GHz, wavelength of 1.875 mm (Figure 1). This microwave, or more appropriately millimeter-wave energy, is everywhere in our current universe. It is the unseen and unfelt backdrop to all other coherent or incoherent energy sources we experience (light, heat, radio waves, etc.) and represents a lower limit to what we would measure if we were able to sense this thermal background directly. Admittedly, the total power is extremely low. Even integrating over the whole output spectrum using the Stefan-Boltzmann relationship it is only a few microwatts/m^2 (radiant emittance, $E = \sigma T^4$, with $\sigma = 5.67x10^{-8}$ W/m^2/K^4 and T the temperature in K). On the Earth, this Cosmic Microwave Background (CMB) energy is totally overpowered by our own thermal background that peaks (when we are comfortably indoors, at least) at a wavelength closer to 9.7 microns (17.6 THz), but which generates significant power ($\approx$150W/m^2) compared to the CMB's, which is one hundred million times weaker - although still the dominant energy form in the universe!

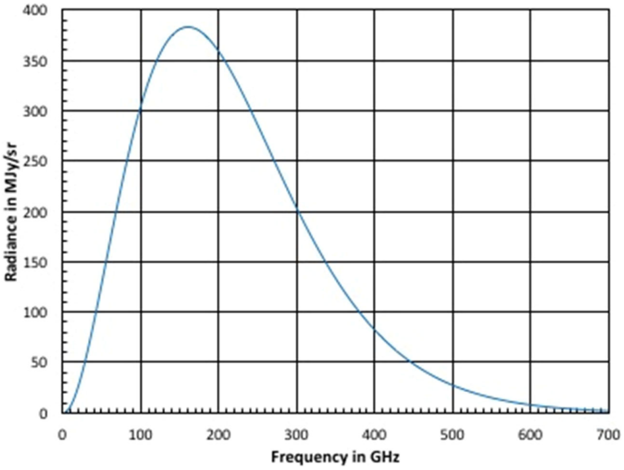

FIGURE 1. Plot of radiance $B(f, T)$ vs. frequency for a black body with T = 2.725 K using Planck's Law (1 MJy = 10^{-20}W/m^2/Hz).

The prediction and discovery of this cosmic microwave background begins in what can only be described as the golden age of modern cosmology, when the likes of Einstein and Lemaître, Hubble and Slipher, Alpher and Herman, Hoyle and Gamow, were debating and delineating the very origins and structure of the universe. We will take a short look at where the CMB originates, where it fits into early and prevailing theories about the origins of the universe, how it was first detected and why it took almost 30 years to measure the full spectrum. We end with current experimental programs to refine CMB measurements so as to bring out extremely small anisotropies and answer even more detailed questions about the nascent, present, and predicted future structure and evolution of the universe.

II. EARLY PREDICTIONS OF THE CMB

The initial concept of the CMB is intimately tied to the idea of a universe that began with a "bang" – although now we think of it more as a smooth expansion. This concept involves multiple threads coming together, coupling difficult and time consuming astronomical observations with general relativity theory, all starting around the beginning of the twentieth century.

In the early 1900's, astronomers did not know for certain whether the stars, clusters and gaseous nebulae they could see through their ever more capable optical telescopes were local to the Milky Way or part of a larger, more complex cosmos. The only method for determining distances to these objects was through parallax measurements (angular shift of nearby objects against a stable background using observations at opposite sides of the Earth's orbit), and only the closest stars had measurable angular shifts. Spectral measurements were well developed and key emission and absorption lines from gaseous elements in the Sun and other stars (hydrogen and helium in particular) were well cataloged. Spectral shifts due to the Doppler effect were also well understood and known to correlate with velocity towards or away from the observation point.

The first long duration spectral observations of large numbers of gaseous nebulae were made by Vesto Slipher between 1912 and 1917, using the Alvan Clark 24-inch refracting telescope at the Lowell Observatory in Flagstaff, Arizona, USA. Slipher showed that most of these "as yet to be fully understood" objects were moving away from the Earth at velocities much greater than the motions of measured stars [3]. Using a slit-spectrograph and camera, with 20-40 hour exposure times, he measured the Doppler shift in the bright and dark line spectra of more than 25 spiral nebulae, and concluded from their mostly redshifted hydrogen sequence lines, that their average velocity of recession was 570 km/sec, almost thirty times faster than known stars. Slipher's statement [3] that, "*It has for a long time been suggested that the spiral nebulae are stellar systems seen at great distances. This is the so-called "island universe" theory, which regards our stellar system and the Milky Way as a great spiral nebula which we see from within. This theory, it seems to me, gains favor in the present observations.*" represents the first experimental evidence for an expanding universe composed of individual galaxies.

Cepheid stars, so named because of their first identification in the constellation of Cepheus in the late 1700's, undergo large, but regular changes in their brightness on a repeating cycle, typically lasting hours or days. We now know this is due to radial pulsations with accompanying changes in brightness and temperature driven by changes in ionized helium in the stars' outer atmosphere. Cepheid stars in the Magellanic Clouds had been shown to have a direct correlation between their pulsation period and their brightness by Henrietta Swan Leavitt in 1908, working at the Harvard College Observatory under Edward Pickering [4], [5]. Since all the Cepheid variables in the Magellanic Clouds were assumed to be of approximately equal distance, Leavitt realized the period, which directly correlated to the object's innate brightness (and hence to its mass), could serve as a yardstick to their distances, assuming the distance to the Magellanic cloud could be independently and accurately determined – which it only very recently was, from the measurements of eclipsing binary stars with known luminosity and diameter [6].

When Edmund Hubble completed his breakthrough observations of spiral galaxies in 1929 [7], using the 100 inch Hale telescope at Mount Wilson, Pasadena, CA, USA – the largest reflecting telescope of the time – he confirmed Slipher's observations through redshift measurements, and more importantly, added confirming evidence of galactic distances through the measurements of Cepheid variables in many of the closer galaxies. In particular, he showed that the Andromeda Nebula was a separate galaxy [8].

Using the Cepheid yardstick, and correlating distance with observed redshift, Hubble derived a linear speed vs. distance relationship for bright stars and nebulae of approximately 500 km/s/megaparsec. He derived a simple relationship (valid to this day), where the recession velocity, V, of a galaxy as determined by its spectral redshift, is proportional to its distance, D, via $V = H_0 D$, where H_0 is now known as the Hubble constant. This provided direct evidence for the idea of an expanding observable universe, a concept which had been independently derived from Einstein's general relativity formulations by Alexander Friedmann in 1922 [9] and popularized by Abbé G. (Georges) Lemaître in 1927 [10]. Hubble's redshift vs. distance and velocity plot [7], now known as Hubble's Law, or more formally as the Hubble-Lemaître law, had H_0 much higher than modern estimates, which puts it at a bit less than 70 km/sec/megaparsec. The discrepancy was largely due to the fact that the Cepheids in distant galaxies turned out to be of a different type than those Leavitt had found in the Magellanic Clouds. Never-the-less, his was an impressive experimental program, and Hubble himself, although he did not conclude directly in his paper [7] that the experiments confirmed an expanding universe, did hint at the impact of the observations on what would later be the Einstein-de Sitter cosmological model.

After the release of Hubble's paper, Lemaître used Slipher's observations to come up with an equivalent of Hubble's constant of 625 km/s/megaparsec [11]. In a very widely read three-quarter column letter in *Nature* in March 1931 [12], followed by a longer discussion in October [13], he suggested the foundation for the Big Bang Theory. Lemaître wrote [12], "*We could conceive the beginning of the universe in the form of a unique atom, the atomic weight of which is the total mass* *of the universe*," and in [13], "*A complete revision of our cosmological hypothesis is necessary, the primary condition being the test of rapidity. We want a 'fireworks' theory of (cosmic) evolution.*" These ideas were so exciting at the time, that there was a half-column write up in the *New York Times* when Lemaître came to Mount Wilson Observatory and gave a talk at Caltech on December 10, 1932 [14].

Albert Einstein and Dutch mathematician, Willem de Sitter, took up Lemaître's inflationary "unique primordial atom" concept and incorporated Hubble's constant when they published the Einstein-de Sitter model of an expanding infinite universe [15]. This model is matter dominant, has minimal or no spatial curvature, and has a vanishing cosmological constant [16].[1] For their expansion period (represented by spectral line redshifts of $z = (\lambda_{meas}\text{-}\lambda_{act})/\lambda_{act}$, between 2 and 300 [17]), and using Hubble's inflated value of 500 km/s/megaparsec (the best estimate at the time), they derived for the early cosmos (the time after the initial explosion, when sufficient expansion and cooling had occurred so that elementary particles – electrons, protons, and neutrons, leptons, bosons, gluons, etc. - could begin to condense to form elements), a cubic volume of 10^6 light years on a side, a density of $4\text{x}10^{-28}$ gm/cm^3, and a mass of $2\text{x}10^{11}$ suns [15].

Not surprisingly, the idea of a single-atom origin for the universe was not unanimously accepted, and competing theories had emerged by the end of World War II. Lemaître's ideas were contrasted by a growing movement of so called "Steady State" advocates, led by the British astronomer Fred Hoyle [18] and Cambridge astrophysicists, Hermann Bondi and Thomas Gold [19]. In the Steady-State universe the density was constant with time, and matter was spontaneously created to keep it so, as the universe expanded in accordance with the Hubble-Lemaître law. Advocating for the Lemaître model were cosmologists George Gamow, Ralph Alpher and Robert Herman, whose three short papers [20]–[22] in 1946-48, outlined their thoughts on the creation of the elements, and later, the stars and galaxies, from the primordial soup that was the result of the Lemaître "fireworks."

Ultimately, predictions of the manifestations of the dramatic explosion and subsequent expansion of Lemaître's primordial-atom universe, and the chance experimental discovery of its remnant thermal signature, led to the general acceptance of the Gamow-Alpher-Herman model. The name, "Big Bang" as applied to the Lemaître concept, was actually coined by Fred Hoyle in a BBC Radio broadcast in March 1949, where he referred to his rival's theory as that "*big bang idea*" [23].

III. TEMPERATURE OF THE UNIVERSE

Between 1949 and 1965 there were few references to the "Big Bang" in the literature, although the term "ylem" was coined by Ralph Alpher [24][2] to represent the "soupy" environment of elementary particles immediately after the explosion, that would eventually cool and condense to form the basic elements. In their *Nature* letter that addresses the mass and energy density of the universe after the expansion of the Lemaître primordial atom, and where they postulated that basic elements were condensing at around 10 million years, Alpher and Herman [22] first proposed a background temperature for the early universe, and extrapolated it forward to present day. They detailed their calculations in a more comprehensive paper [25] using the Einstein-de Sitter model for the changing mass and energy densities in the universe over time, and plotted the corresponding temperature from the period just after the primordial atom out to approximately 30 billion years.

At the beginning there were only elementary particles – electrons, neutrons and protons, etc. confined at very high temperatures. During the early stage of expansion alpha particles were formed. Thermal photons would be totally scattered (mainly by the free electrons) and never leave the expanding volume. At some point (now judged to be about 380,000 years), the density decreased sufficiently, and the corresponding temperature dropped to a level (roughly 3000 K) where electrons could combine to form hydrogen and helium. This condition allowed thermal energy in the form of photons, to fill the space and reduce their strong interactions with the contained matter.

Over time, and due to the velocity of expansion and resulting redshift, the observed radiance from the hot condensing matter took the form of a blackbody spectrum whose energy peak shifted from roughly 2 microns (at the recombination time) out to approximately 2 mm in present day, but maintained its characteristic shape as shown in Figure 1 [26]. In terms of the redshift, $z = (\lambda_0\text{-}\lambda_t)/\lambda_t$, where λ_t is the wavelength at any time after CMB emission, and λ_0 is the wavelength at present, the CMB temperature, T, is simply: $T(z) = T_0(1+z)$, with T_0 the current value. The baryon mass density (protons and neutrons), n, at any time is then: $n(z) = n_0(1+z)^3$, where n_0 is the density in present day [27]. With the Hubble-Lemaître law and the Einstein de Sitter relativity formulations, Alpher and Herman calculated the current mass density of the cosmos to be between 10^{-29} and 10^{-30} gm/cm^3, and the equivalent Doppler shifted background temperature from the recombination period, as observed today, to be between 1 and 5 K [25].

IV. SEARCH FOR THE CMB

Following the calculations by Alpher and Herman, there were appeals to experimental astronomers to look for the residual

---

[1] The cosmological constant, Λ was a term that Einstein added to his General Relativity theory in 1917 to counteract the effects of gravity and result in a static universe. It represents the vacuum energy density of space, now generally associated with dark energy. When Hubble's evidence of an expanding universe was published, Einstein was able to remove this term in the equations and mimic the expansion in the Einstein-de Sitter model. Einstein and de Sitter state, *"λ was introduced into the field equations in order to enable us to account theoretically for the existence of a finite mean density in a static universe."* [14]. Note, Einstein's λ is now generally written as Λ in cosmological models.

[2] From [24, footnote 17, p. 1581]: "According to Webster's New International Dictionary, 2nd Ed., the word "ylem" is an obsolete noun meaning "The primordial substance from which the elements were formed." It seems highly desirable that a word of so appropriate a meaning be resurrected."

background energy from the big bang. The predicted 1-5 K radiation peak would be in the millimeter-wave regime (60-300 GHz), but nascent radio astronomers were having sufficient difficulties getting the necessary receiver sensitivity to detect the very strong neutral hydrogen spin transition at 21 cm (1420.4 MHz), first detected in 1951 by Ewan and Purcell [28], and the technology was not quite developed enough to detect the much higher frequency millimeter- and submillimeter-wave signals.

Despite the limitations in receiver technology, there were several near discoveries of the CMB, including the reporting of an isotropic background temperature of 3 K ±2 by Emile le Roux after a 33 cm (900 MHz) sky survey using the Nançay Radio Observatory in central France in 1955 [29], and a Russian PhD thesis in 1957 by Tigran Shmaonov, that reported a radiation background temperature of 4 K ±3 at 3.2 cm (9.35 GHz) observed for cold space [29]. However, it was not until 1964, with the careful radiometry measurements of Arno Penzias and Robert Wilson, that the cosmic black body radiation was detected and simultaneously attributed to a signature from the big bang.

V. PROOF OF A BLACKBODY REMNANT

In 1963, Robert Wilson, after completing a PhD thesis and post-doc at Caltech in Pasadena, California, drove across the US to join the radio astronomy team under Roy Tillotson at Bell Laboratories, Crawford Hill, N.J. [30]. Wilson began working with radio engineer, David Hogg, on making highly accurate gain measurements on the Bell Lab's 20-foot square-aperture horn antenna [31] using a very sensitive 4 GHz (7.3 cm) helium-cooled traveling-wave maser amplifier-based receiver system [32]. Taking advantage of the well calibrated antenna and receiver, Wilson began working with colleague Arno Penzias, to make accurate flux measurements of known cosmic radio sources [33]. The antenna and flux measurements had practical significance to Bell Laboratories for the calibration of communications satellite antennas, as well as to radio astronomers studying the cosmos.

As Wilson and Penzias worked through their antenna and receiver noise calibration terms to quantify the radio flux they were measuring from their astronomical sources, they ran into a persistent background signal with an effective noise temperature of 3.5 ±1 K that did not go away when they turned the antenna to cold space, and was the same magnitude no matter what direction in the sky they looked. They were using a Dicke-switched receiver [34] with a very precise helium load built by Penzias, which assured extremely accurate overall noise temperature calibration measurements. Fortuitously, at an astronomy conference in Montreal in late 1964, Penzias spoke with MIT cosmologist Bernard Burke about the background noise issue, and a few months afterwards, Burke relayed a draft copy of a paper by Robert Dicke, Jim Peebles, Peter Roll and Dave Wilkinson at Princeton University, on a prediction of a blackbody signature from the Big Bang that fit with the excess noise characteristics Penzias and Wilson had observed [35]. After several phone calls, and a visit by the Princeton team to Crawford Hill, the two groups decided to publish back-to-back articles on their findings in the *Astrophysical Journal* which appeared in November 1965 [36], [37]. Note, that although Dicke attributed the 3.5 K noise from the Penzias and Wilson data, as coming from the thermal blackbody signature of the Big Bang, he had earlier calculated the temperature to be much higher, with an upper limit closer to 40 K [36]. From the perspective of the cosmological theories of the time, the very low value of the CMB temperature measured by the Bell labs team, favored a lower density of matter and a correspondingly smaller gravitational attraction, implying an open universe (continuous expansion) in the Einstein-de Sitter model.

VI. PROBLEMS WITH THE BLACKBODY SPECTRUM

The reported cosmic background noise signal found by Penzias and Wilson at 4080 MHz, represented only one data point on the low end of a predicted blackbody spectral curve that spanned roughly 600 GHz. The search to fill in other frequencies along the curve began immediately, with the Princeton team adding a 9.4 GHz (3.2 cm) point in 1966 [38]. Other microwave measurements from astronomers around the globe were contributed, and by 1977 a pretty good fit to a 2.73 K blackbody spectrum had emerged [39]. A year later, Arno Allan Penzias and Robert Woodrow Wilson would share the 1978 Nobel Prize in Physics for their part in the discovery of the CMB, but Phillip James Edwin Peebles would have to wait until 2019 to partake in their honor. By 2019, Robert Henry Dicke and David Todd Wilkinson had already passed away.

Despite mounting observational evidence of the ubiquitous and constant temperature profile of the CMB, there were still many unanswered questions about the implications of such a spatially uniform thermal signature on theories of the current structure and evolution of the universe. Certain observational details, such as the relative motions of the solar system and the Milky Way, and some early evidence of "clumpiness" in the form of large galactic clusters [40], were predicted to show up as small variations in the CMB temperature profile measured on different spatial scales. There was also the disturbing conclusion that the observable (luminous) mass in the cosmos was grossly insufficient to stop the current expansion through gravitational attraction, and could not account for the gravitational binding of galaxies within a cluster, or even stars within a spiral galaxy [41]. This dilemma had been suggested by Fritz Zwicky at Caltech in the late 1930's from observations at Mount Palomar of the motions of a large cluster of nebulae about their perceived center in the constellation of Coma Berenices. Zwicky found that the visible masses of the nebulae themselves could not hold them at their current orbital distances, and coined the term 'dark matter' to account for the required unseen mass postulated to be in a shell around each nebula. He classified this unobservable matter as "*cool and cold stars, macroscopic and microscopic solid bodies, and gases*" [42].

Further complications for the Big Bang theory came in 1977, when George Smoot, who was using a precision 33 GHz differential radiometer (two antennas pointing in different angular directions and spun 180 degrees around their common central axis at regular intervals for calibration) mounted on a high altitude U2 aircraft platform, to look for a predicted, but very small deviation (~3.5 mK) in the CMB temperature in different spatial directions due to local motion of the Earth. Instead he discovered a very unexpected result: the Milky Way galaxy was moving towards the Leo cluster (a portion of the Coma supercluster – a collection of more than 3000 galaxies in the constellation of Coma Berenices) at 600 km/sec [43], [44]. This observation strongly supported the idea that there was a dense region of galactic space pulling the Milky Way towards it, but with no visual indications of the requisite mass. By 1982, an extensive survey from the Harvard Smithsonian Center for Astrophysics, showed that there was extreme clumpiness in the distribution of galaxies. In fact, dense strings of galaxies were concentrated at different redshifts with large voids at other distances and times [45].

At this point in the experimental measurements of the CMB, there was no indication of any spatial anisotropy that would be the result of primordial variations in the energy distribution. However, a fully isotropic CMB, with no spatial variations, resulting from a single step expansion with subsequent condensation (recombination of protons, electrons and neutrons) and release of thermal photons some 300,000 years afterwards, did not account for the observed clumpiness of the galaxies in space and time. Furthermore, the size of the early condensation sphere meant that any local variations in temperature could not be communicated to different points in the sphere quickly enough for thermal equilibrium to be reached. This was because the diameter of the observable universe at the time of recombination was calculated to be more than $5\text{x}10^7$ light years based on redshift data. This implied that the distance that particles could have travelled at the speed of light within the time since the big bang would have been only around $3\text{x}10^5$ light years, or only a couple of degrees around the sphere. This is known as the horizon problem. Unless there was a mechanism that allowed for photon interaction across the diameter of the recombination sphere, there should be significant observable temperature variations in the CMB when looking at different points in cold space on an angular scale greater than a few degrees.

A solution to the anisotropy question was developed by American cosmologist, Alan Guth in 1981 [46], who postulated a two stage Big Bang, with a very brief exponential growth period followed by the postulated expansion represented by the Hubble Law. This short hyperinflationary period, from the primordial atom out to only about 10^{-32} sec, at which time the diameter of the observable universe was only a few cm, allowed thermal equilibrium to occur, resulting in a much more uniform CMB. This hyperinflation concept also supported a flat universe (zero gravitational curvature) as well as the lack of observable magnetic monopoles (they were all created and left behind in the hyperinflation region, so do not appear locally). In the Guth model, the observed level of CMB temperature variation which would eventually give rise to galaxies and the observed clumpy universe, was much lower than predicted in the standard single-stage Big Bang model, and from much later measurements [47], would turn out to be on the order of only one hundred microKelvin!

This level of sensitivity to temperature variation, the need to cover many directions in space without atmospheric fluctuations or receiver positional bias, and the requirement of measuring the full CMB spectrum with extreme power stability and wavelength accuracy, consistently and over a very long observation period, pushed astronomers and especially cosmologists, to lobby for a space-based CMB mission.

VII. COBE: FULL CMB SPECTRUM AND ANISOTROPY

NASA's Explorer program had a long history of astronomical and space-science based discoveries, beginning with the Van Allen radiation belt, first observed from Explorer 1 in 1958. The 1974 Explorer instrument program call received three proposals related to the CMB: one from Lawrence Berkeley National Laboratory (George Smoot and Luis Alvarez), one from Jet Propulsion Laboratory (led by Sam Gulkis and Mike Janssen), and one from Goddard Space Flight Center (PI'd by Mike Hauser and with team member John Mather, then a post-doc at the NASA Goddard Institute for Space Studies in NYC). That year, the NASA call was won by the Infrared Astronomy Satellite (IRAS) proposal [48], but NASA was sufficiently interested in the CMB science to assemble a study group and engineering team in 1976, composed of members of all three CMB proposal teams.

The CMB study group came up with a mission proposal consisting of three instruments: FIRAS (Far Infrared Absolute Spectrophotometer), to record the full CMB spectrum plus thermal emission from gas and dust and key interstellar molecular line emissions from 100-2900 GHz; DMR (Differential Microwave Radiometer), to measure CMB anisotropy down to one part in 10^5 at 23, 31.5, 53 and 90 GHz; and DIRBE (Diffuse Infrared Background Explorer), to map the total background infrared emission from dust in the Milky Way between 1 and 240 microns wavelength [49]. By 1980, this complement of instruments had been assigned to an Explorer mission (Explorer 66) and named COBE (Cosmic Background Explorer) with a launch date of 1988 from the Space Shuttle. John Mather, now working at Goddard Space Flight Center in Greenbelt, Maryland, was the Principal Investigator for FIRAS. George Smoot directed DMR with Deputy PI Chuck Bennett, and Mike Hauser, was the PI for DIRBE. The mission and instrument development were to be run out of NASA Goddard. Members of the original three 1974 proposal teams were integrated into teams for the three selected instruments.

The 1986 Challenger disaster, followed by two failed conventional rocket launches in the US, almost cancelled the mission. The COBE team started looking for alternative launch vehicles and even approached the European Space Agency [35]. NASA scrambled to find an alternative to the space shuttle, and eventually moved the satellite to one of its last available small Delta rockets. Fitting into the smaller payload volume of the Delta required an enormous redesign effort with a significant reduction in mass and volume. According to Smoot [50], it was one of the greatest engineering challenges ever undertaken by Goddard. COBE was launched on Nov. 18, 1989 from Vandenburg Air Force base in southern California, into a Sun-synchronous polar orbit that allowed full sky coverage and complete Sun-Earth shielding for the superfluid-Helium cryostat carrying the instruments [51].

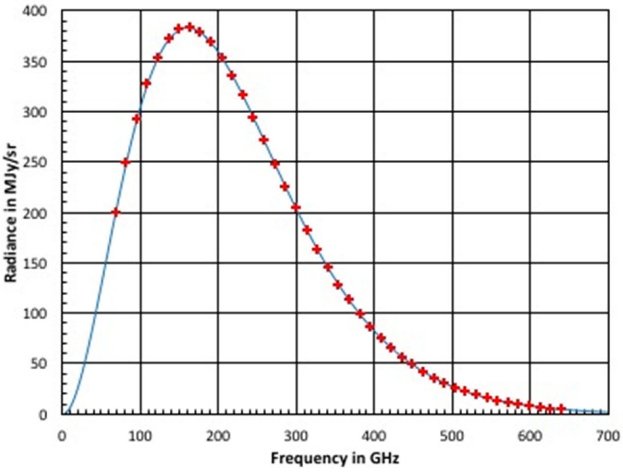

FIGURE 2. Plot of radiance vs. frequency for COBE data (crosses) and a 2.725 K blackbody (line) *(from FIRAS CMB Temperature Map data [58].*

Between 1981 and the launch of the COBE satellite, continued work on the CMB from high altitude balloon platforms and sounding rockets had resulted in two particularly intriguing findings. Independent groups at Princeton led by Dave Wilkinson [52], and from Rome, Italy led by Francesco Melchiorri [53], both reported detecting very weak (10^{-4}) fluctuations in the CMB temperature profiles. Also a team from UC Berkeley (Paul Richards [54]) and Nagoya University in Japan (Satio Hayakawa), equipped and launched a series of short duration rocket sounders, and reported a potential deviation of the CMB from a perfect blackbody curve in the submillimeter-wave regime above 300 GHz [55], [56]. Several follow-up attempts to confirm both of these findings at ground based observatories had not been successful.

Two months after COBE was launched, the FIRAS instrument had already returned sufficient data that the first results could be reported. FIRAS used a superfluid Helium cooled (1.5 K) scanning polarizing Michelson interferometer to create interferograms spanning 30-2900 GHz with a resolution of 6.9 GHz. The detectors were composed of custom high sensitivity and robust silicon composite microbolometers fabricated by NASA Goddard's Aristides Serlemitsos [57]. Data products included the CMB temperature profile; emission line maps of key interstellar molecules, including the important C II line of ionized carbon (C^+) at 1.9 THz, two N^+ emission lines at 2.46 and 1.46 THz and the J = 2,3,4 and 5 rotational transitions of CO, as well as many other species; and interstellar dust spectra. The science community's first glimpse at the CMB blackbody curve came at the January 1990 meeting of the American Astronomical Society, when John Mather presented a version of Figure 2 to an applauding crowd of over 1000 people in Washington DC.

Immediately after John Mather spoke at the conference, George Smoot presented the first two months of data from DMR. The results confirmed the dipole anisotropy Smoot and colleagues had already demonstrated as being due to galactic motion in 1976 [43], and set an upper limit to the predicted non-motion based anisotropy which was lower than, and therefore refuted, the Wilkinson [52] and Melchiorri [53] measurements. It would take another 2 years before data from DMR was complete enough, and the COBE DMR team had sufficient measurements on the background emission from the Milky Way (which had to be subtracted from the CMB signal at all spatial points to allow any innate signal differences to be flushed out), to make a more quantitative and definitive announcement on the anisotropy question.

Calibrating out the galactic contributions and all the other potentially unrelated background and instrument related signals to the CMB in order to bring out any differential temperature structure, proved to be extremely difficult. Edward L. (Ned) Wright produced the first maps showing the cosmic fluctuations, and DMR deputy PI, Chuck Bennett and Gary Hinshaw, led the cross-checking process to test that they were correct. They were also able to make use of, and compare COBE data with a supporting 19 GHz balloon program [59] that covered a very small region of the total sky, but at a resolution consistent with COBE. Smoot and LBNL colleagues took off for Antarctica to make independent measurements of the galactic plane at all the COBE DMR receiver frequencies using a large 10 meter telescope that had been assembled there in 1991. This was one of the few places on Earth where atmospheric water vapor absorption was consistently low enough in the millimeter-wave region to allow the stable and sensitive ground based observations that were required for the removal of this background signal from the DMR data. The news-making report on the first confirmed measurements of anisotropy in the CMB, as made by the DMR instrument on COBE, came at the American Institute of Physics conference in April 1992 where a picture of these minute temperature variations (at a lower limit of 1 part in 10^5) was presented [60]. Figure 3 shows the CMB temperature variations from the COBE DMR as shown on the NASA website [61].

The observed fluctuations in the CMB were solid evidence for the early structural seeds of galaxy formation and an almost insurmountable body of support for the Big Bang theory. The result also further whet the appetites of cosmologists around the world to propose follow-ons to COBE: ground based, balloon and satellite instruments, in order to gain a much higher resolution picture of the anisotropy (COBE

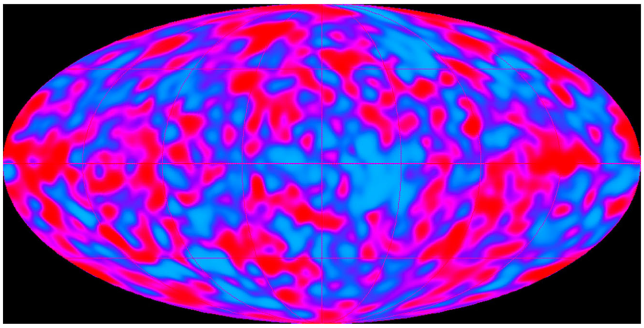

FIGURE 3. **Temperature map of the CMB with a color variance of 1 part in 100,000 above and below the nominal 2.725 K. The plane of the Milky Way is across the center, Orion is on the right and Cygnus on the left.** ***(from NASA LAMBDA-Data Products, DMR Images [61]).***

DMR only had a 7 degree angular resolution). These follow-on instruments provided even higher temperature sensitivity at greater angular resolution, and added measurements of predicted polarization variations that would help refine the cosmological models and provide details to the evolutionary path the cosmos has taken since the expansion of Lemaitre’s primordial atom.

VIII. WMAP: CMB ANISOTROPY

A space mission focused directly on the anisotropy of the CMB was proposed by several groups in the mid 1990’s to take advantage of a new mid-scale NASA Explorer satellite mission queue. Three principal mission concepts were proposed: one from Caltech, one from JPL, and one from COBE deputy PI, Charles Bennett and the cosmology team at Princeton University led by David Wilkinson and Lyman Page. It was the Bennett-Wilkinson Microwave Anisotropy Probe (MAP) that would ultimately win the proposal.

The goals for MAP were to “map” the CMB variations across the full sky at an angular resolution of better than 0.3 degrees (compared to COBE’s 7 degree resolution) at a temperature sensitivity of less than 1 milli-Kelvin/Hz$^{1/2}$ (compared to 15-45 milli-Kelvin/Hz$^{1/2}$ on COBE) [62], [63]. These goals were extraordinarily ambitious. Consider the sheer number of individually integrated radiometric observations (each 50-100 msec) entailed by the 0.3-degree sky resolution – more than 3 million precisely overlapping points, over a large number of wavelengths and with a differential temperature stability more than 2000 times better than COBE’s DMR! MAP also introduced a new detector concept to space systems, passively cooled high electron mobility transistor (HEMT) amplifiers, for its five simultaneously sampled radiometer bands between 23 and 94 GHz. MAP carried a total of 10 separate 4-channel differential heterodyne receivers (four at 90 GHz, two at both 41 GHz and 61 GHz, and one each at 23 and 33 GHz). The optical beam was produced by a Gregorian telescope with a 1.4x1.6 m primary reflector and the receiver compartment was passively cooled to below 95 K in an L_2 orbit to reduce detector noise and improve thermal stability. The lowest frequency channels at 23 GHz had a resolution of just below 1 degree, and the 94 GHz receivers had the maximum resolution of 0.23 degrees [64]. MAP was launched in June 2001 and operated until August 2010. In 2002, Wilkinson passed away and the team had the mission renamed WMAP in his honor. Even compared to COBE, it would be a spectacular success.

During the time between the results announced from COBE and the launch of WMAP, a lot had happened in the cosmology world. The search for ever smaller differential temperature variations and fine scale structure (to account for galaxy formation) in the CMB continued with both ground- and balloon-based observatories [65], [66]. An entirely new observational goal was introduced to find predicted acoustic wave variations in the CMB [67], [68]. Acoustic wave signatures were predicted to arise from baryon-photon interactions in the recombination sphere that caused the primordial gas to compress and expand, therefore to heat and cool, in a periodic fashion. These fluctuations would be manifested as amplitude “waves” in the CMB temperature spectrum that peaked at different angular scales with the primary peak (largest differential temperature ratio) occurring at a scale of one degree [69]. The one degree peak was beautifully revealed in a well-publicized [70] high altitude balloon observatory flight from the South Pole, led by Andrew Lange at Caltech and Paolo de Bernardis at University of Rome, and nicknamed Boomerang (Balloon Observations of Millimetric Extragalactic Radiation and Geophysics), in 1999 [71]. Subsequent 2nd and 3rd order peaks were confirmed by an interferometric array program, Cosmic Background Interferometer (CBI), in the Chilean Andes, operating from 26-36 GHz, and also led by a Caltech team [72]. Implications for the findings would pin down the expansion rate, density of regular and dark matter, and whether the universe was truly flat (as confirmed by the Boomerang team), or contained significant curvature.

In addition to the CMB power spectrum observations, Adam Riess at Berkeley, Brian Schmidt at Harvard, and Saul Perlmutter at Lawrence Berkeley National Laboratory, used Stirling Colgate’s earlier work on supernovae as probes for galactic distance [72], to conclude, to the surprise of most cosmologists, that the observable universe was expanding at a faster rate today than it had been in the past [74], [75]. This astonishing result led to their receiving the 2011 Nobel Prize in Physics and to the concept of “dark energy” a new phenomenon postulated to be driving an acceleration in the expansion of the matter in the cosmos.

A final experimental breakthrough impacting cosmology came out in 2002 from a team at University of Chicago led by astronomer John Carlstrom using a radio telescope array in Antarctica nicknamed, Degree Angular Scale Interferometer (DASI). The DASI group published the first observations of an intrinsically polarized anisotropic CMB [76]. These results validated calculations that an anisotropic thermal distribution in the recombination sphere would result in a weak but

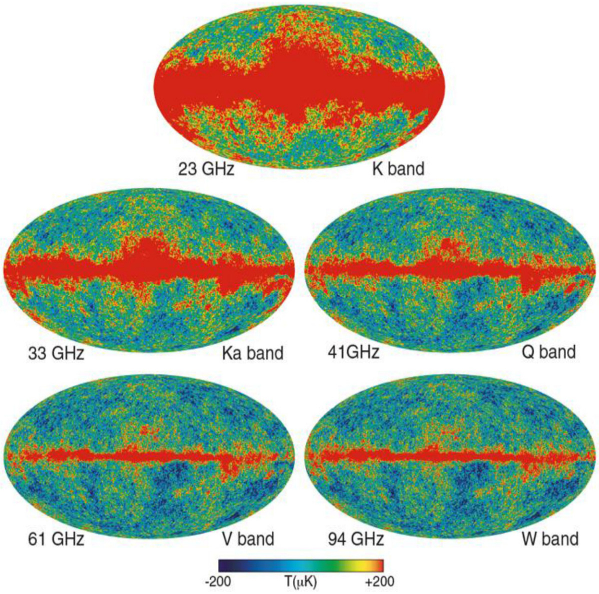

FIGURE 4. **Temperature maps of the CMB variations with a deviation of ±200 microK scale at all 5 WMAP frequency bands** ***(from NASA Lambda-Data Products and [77], WMAP Science Team).***

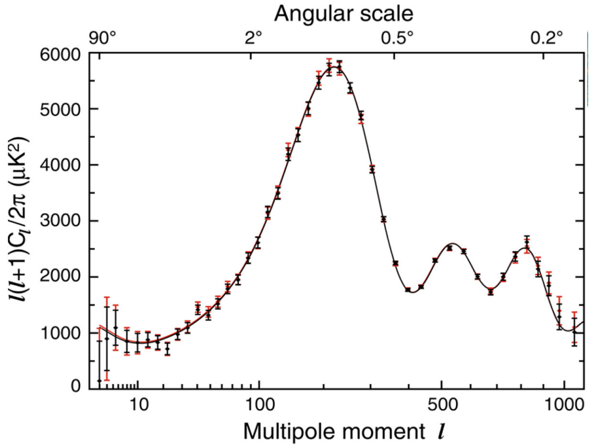

FIGURE 5. **CMB power spectrum with WMAP data superimposed. The acoustic peak at an angular scale of ≈1 degree indicates a flat universe. 2nd and 3rd degree peaks are also shown.** ***(from NASA Lambda-Data Products and [78], WMAP Science Team).***

persistent polarization signature from the Thomson scattering of varying energy photons off the free electrons.

WMAP brought all these observations together and reduced many long-standing uncertainties in the cosmological models. The first full sky maps were released in 2003, and they continued to be refined and upgraded with additional observations through to the end of the mission in 2010. Some final 9-year data CMB maps are shown in Figure 4 [77] and the CMB power spectrum fit to the acoustic wave angular scale data is given in Figure 5 [78]. In addition, WMAP assigned values to many cosmological parameters with much higher accuracy than any prior measurements. These included a value of 70 km/s/megaparsec for the Hubble constant, 13.74 billion years for the age of the universe, 377,000 years for the beginning of the recombination period, and 0.046, 0.233 and 0.721 for the densities of Baryonic-based matter, dark matter and dark energy relative to the critical density, ρ_c (the density representing a flat universe with no spatial curvature and a cosmological constant = 0), where $\rho_c \approx 1$ [77], [78].

After WMAP, the European Space Agency's Planck Mission added even more detailed CMB anisotropy plots [79] and an enormous amount of high resolution all-sky data supporting the hyperinflation model, confirming the density and overall percentage of dark matter in the universe, yielding evidence for the fluctuations that have given rise to present galactic cluster formation, and many more achievements [80]. Planck ruled out many of the competing hyperinflation models but it, and many ground and balloon-based measurements which followed, continue to provide additional details which support the Big Bang with hyperinflation, although the exact mechanisms are still poorly understood.

Most recently, efforts are being focused in at least two major areas. The first is on very accurately measuring the Sunyaev-Zel'dovich effect [81], a slight distortion of the intensity and frequency spectrum of the CMB as it passes through galactic clusters, which can give a more precise value to the Hubble constant. The second is on precision polarization measurements of the CMB to detect the presence of gravitational waves which are predicted to occur in the hyperinflation model [82] and which can also show the presence of gravitational lensing [83]. Both of these pursuits are being carried out by major ground-based observatories in the Andes: Atacama B-Mode Search [84] and POLARBEAR on the Huan Tran Telescope [85], and at the South Pole: BICEP - Background Imaging of Cosmic Extragalactic Polarization and Keck Array Telescopes [86], [87], as well as observations from space based platforms like the Herschel Space Observatory [88].

This continuing interest in the CMB and the need for ever more sophisticated instruments to measure the subtle differences in the observed spectra has spurred an incredible surge in new high tech telescope instruments and detector techniques [89] from which astronomers worldwide are benefitting.

For cosmologists – and all of us who want to understand how we came to be – there are almost as many unanswered questions and new puzzles to piece together as ever, not the least of which are what really constitutes dark matter, and what gives rise to, and what are the properties of dark energy. However, at this point, we are already well beyond the intent and scope of this basic review of how we came to realize that "*Microwaves are Everywhere*".

IX. CONCLUSION

Hopefully, this short history and description of the cosmic microwave background will give the reader a cursory understanding of the place and importance of microwaves in our world. Our understanding and interpretation of the origins of the universe are – appropriately – continuously evolving, and therefore are likely to change as our current theories are honed and our experiments become more sophisticated. However we end up ultimately interpreting the CMB, the fact that the cosmos is bathed in microwave energy will hold constant. *Microwaves are Everywhere* is just as certain today as it was 13.4 billion years ago!

ACKNOWLEDGMENTS

The author thanks Dr. Heather Lee, Pasadena, CA, USA, for discussions on relativity and initial review. He also thanks and appreciates a read-through of the initial submitted manuscript by Dr. John Mather with returned comments, corrections, and many excellent suggestions for improving the article. The author highly recommends two excellent books and a chapter/review article with lots of technical details and references (see [90] and [91]). Interested lay readers are highly encouraged to access the very readable book by University of Cardiff astronomer, Rhodri Evans, from which much of this article is structured (see [35]).

REFERENCES

[1] J. C. Mather *et al.*, "Measurement of the cosmic microwave background spectrum by the COBE FIRAS instrument," *Astrophys. J.*, vol. 420, pp. 439–444, Jan. 1994, doi: 10.1086/173574.

[2] D. J. Fixsen, E. S. Cheng, J. M. Gales, J. C. Mather, R. A. Shafer, and E. L. Wright, "The cosmic microwave background spectrum from the full COBE FIRAS data set," *Astrophys. J.*, vol. 473, pp. 576–587, Dec. 1996, doi: 10.1086/178173.

[3] V. M. Slipher, "Nebulae," *Proc. Amer. Phil. Soc.*, vol. 56, pp. 403–409, Apr. 2017.

[4] H. S. Leavitt, "1777 variables in the Magellanic Clouds," *Ann. Harvard College Obs.*, vol. 60, no. 4, pp. 87–108, 1908.

[5] E. C. Pickering (with work attributed to H.S. Leavitt), "Periods of 25 variable stars in the small Magellenic Cloud," *Harvard College Obs., Circular*, vol. 173, Mar. 1912.

[6] G. Pietrzynski *et al.*, "A distance to the Large Magellenic Cloud that is precise to one percent," *Nature*, vol. 567, pp. 200–203, Mar. 2019, https://doi.org/10.1038/s41586-019-0999-4

[7] E. Hubble, "A relation between distance and radial velocity among extra-galactic nebulae," *Proc. Nat. Acad. Sci.*, vol. 15, no. 3, pp. 168–173, Jan. 1929, doi:10.1073/pnas.15.3.168.

[8] E. P. Hubble, "Cepheids in spiral nebulae," *Observatory*, vol. 48, pp. 139–142, May 1925.

[9] A. Friedman, "Über die krümmung des raumes," {translation: On the Curvature of Space}, *Zeitschrift für Physik*, vol. 10, no. 1, pp. 377–386, Dec. 1922, doi: 10.1007/BF01332580.

[10] A. G. Lemaître, "Un univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques," *Annales de la Société Scientifique de Bruxelles*, vol. A47, pp. 49–59, 1927.

[11] A. G. Lemaître, "Expansion of the universe, A homogeneous universe of constant mass and increasing radius accounting for the radial velocity of extra-galactic nebulae," *Monthly Notices Roy. Astron. Soc.*, vol. 91, no. 5, pp. 483–490, Mar. 1931, doi: 10.1093/mnras/91.5.483.

[12] A. G. Lemaître, "The beginning of the world from the point of view of quantum theory," *Nature*, vol. 127, no. 3210, p. 447, Mar. 1931.

[13] A. G. Lemaître, "Contributions to a British Association discussion on the evolution of the universe," *Suppl. Nature*, vol. 128, pp. 704–706, Oct. 1931.

[14] "Finds no conflict of science, religion: Explains universe theory. Belgian scholar tells Pasadena group it began with bursting atom 10 billion years ago," *New York Times*, p. 25, col. 3, Sunday, Dec. 11, 1932.

[15] A. Einstein and W. de Sitter, "On the relation between the expansion and mean density of the universe," *Proc. Nat. Acad. Sci.*, vol. 18, no. 3, pp. 213–214, Mar. 1932.

[16] Wikipedia, "Cosmological constant," 2020. Accessed: Jul. 20, 2020. [Online]. Available: https://en.wikipedia.org/wiki/Cosmological_constant

[17] Wikipedia, "Einstein de sitter universe," 2020. Accessed: Jul. 20, 2020. [Online]. Available: https://en.wikipedia.org/wiki/Einstein%E2%80%93de_Sitter_universe

[18] F. Hoyle, "A new model for the expanding universe," *Monthly Notices Roy. Astron. Soc.*, vol. 108, no. 5, pp. 372–382, Aug. 1948.

[19] H. Bondi and T. Gold, "The steady-state theory of the expanding universe," *Monthly Notices Roy. Astron. Soc.*, vol. 108, no. 3, pp. 252–270, Jul. 1948.

[20] G. Gamow, "Expanding universe and the origin of the elements," *Phys. Rev.*, vol. 70, no. 7, pp. 572–573, Oct. 1946.

[21] R. Alpher, H. Bethe, and G. Gamow, "The origin of chemical elements," *Phys. Rev.*, vol. 73, no. 7, pp. 803–804, Apr. 1948, doi: 10.1103/PhysRev.73.803.

[22] R. Alpher and R. Herman, "Evolution of the universe," *Nature*, vol. 162, no. 4124, pp. 774–775, Nov. 1948, doi: 10.1038/162774b0.

[23] S. Mitton, *Fred Hoyle: A Life in Science*. Cambridge, U.K.: Cambridge Univ. Press, 2011, ISBN 978-0-521-18947-7.

[24] R. A. Alpher, "A neutron capture theory for the formation and relative abundance of the elements," *Phys. Rev.*, vol. 74, no. 11, pp. 1577–1590, Dec. 1948.

[25] R. A. Alpher and R. C. Herman, "Remarks on the evolution of the expanding universe," *Phys. Rev.*, vol. 75, no. 7, pp. 1089–1095, Apr. 1949.

[26] R. C. Tolman, *Relativity, Thermodynamics, and Cosmology*. Oxford, U.K.: Clarendon Press, 1934.

[27] P. J. E. Peebles, D. N. Schramm, E. L. Turner, and R. G. Kron, "The case for the relativistic hot Big Bang cosmology," *Nature*, vol. 352, pp. 769–776, Aug. 1991.

[28] H. I. Ewen and E. M. Purcell, "Observation of a line in the galactic radio spectrum: Radiation from galactic hydrogen at 1,420 Mc./sec," *Nature*, vol. 168, no. 4270, p. 356, 1951.

[29] Wikipedia, "Cosmic microwave background," subsection: "Microwave background radiation predictions and measurements," 2020. Accessed: Jul. 20, 2020. [Online]. Available: https://en.wikipedia.org/wiki/Cosmic_microwave_background

[30] P. H. Siegel, "Terahertz pioneer: Robert w. Wilson: The foundations of THz radio science," *IEEE Trans. THz Sci. Technol.*, vol. 2., no. 2, pp. 161–166, Mar. 2012.

[31] D. C. Hogg and R. W. Wilson, "A precise measurement of gain of a large horn-reflector antenna," *Bell Syst. Tech. J.*, vol. 44, no. 6, pp. 1019–1030, Jul.-Aug. 1965.

[32] J. A. Giordmaine, L. E. Alsop, C. H. Mayer, and C. H. Townes, "A maser amplifier for radio astronomy at X-band," *Proc. IRE*, vol. 47, no. 6, pp. 1062–1069, Jun. 1959.

[33] R. W. Wilson and A. A. Penzias, "Measurement of flux of 5 sources at 4080 Mc/sec," *Astron. J.*, vol. 70, no. 9, pp. 697, 1965.

[34] R. H. Dicke, "The measurement of thermal radiation at microwave frequencies," *Rev. Sci. Instrum.*, vol. 17, no. 7, pp. 268–275, 1946.

[35] R. Evans, *The Cosmic Microwave Background, How it Changed our Understanding of the Universe*. Switzerland: Springer International, 2015, ISSN 2197-6651 (electronic), doi: 10.1007/978-3-319-09928-6.

[36] R. H. Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson, "Cosmic blackbody radiation," *Astrophys. J.*, vol. 142, no. 1, pp. 414–419, Nov. 1965.

[37] A. A. Penzias and R. W. Wilson, "A measurement of excess antenna temperature at 4080Mc/s," *Astrophys. J.*, vol. 142, no. 1, pp. 419–421, Nov. 1965.

[38] P. G. Roll and D. T. Wilkinson, "Cosmic background radiation at 3.2 cm-support for cosmic blackbody radiation," *Phys. Rev. Lett.*, vol. 16, pp. 405–407, 1966.

[39] E. I. Robson and P. E. Clegg, "Microwave background spectrum: Survey of recent results," in *Proc. IAU Symp. Radio Astron. Cosmology*, D. L. Jauncey, Ed., Cavendish Lab., Cambridge Univ., U.K., 1977, no. 74, pp. 319–325.

[40] G. de Vaucouleurs, "The distribution of bright galaxies and the local supergalaxy," *Vistas Astron.*, vol. 2, pp. 1584–1606, 1956.

[41] J. P. Ostriker and P. J. E. Peebles, "A numerical study of the stability of flattened galaxies: Or, can cold galaxies survive?," *Astrophys. J.*, vol. 186, no. 2, pp. 467–480, Dec. 1973.

[42] F. Zwicky, "On the masses of nebulae and of clusters of nebulae," *Astrophys. J.*, vol. 86, no. 3, pp. 217–246, Oct. 1937.

[43] G. F. Smoot, M. V. Gorenstein, and R. A. Miller, "Detection of anisotropy in the cosmic blackbody radiation," *Phys. Rev. Lett.*, vol. 39, no. 13, pp. 898–901, Oct. 1977.

[44] M. V. Gorenstein and G. F. Smoot, "Large-angular-scale anisotropy in the cosmic background radiation," *Astrophys. J.*, vol. 244, pp. 361–381, Mar. 1981.

[45] M. Davis, J. Huchra, D. W. Latham, and J. Tonry, "A survey of galaxy redshifts. II. The large scale space distribution," *Astrophys. J.*, vol. 253, pp. 423–445, Feb. 1982.

[46] A. H. Guth, "Inflationary universe: A possible solution to the horizon and flatness problems," *Phys. Rev. D*, vol. 23, no. 2, pp. 347–356, 1981.

[47] National Aeronautics and Space Administration, "WMAP: CMB images." Accessed: Sep. 15, 2020. [Online]. Available: https://map.gsfc.nasa.gov/media/101080/index.html

[48] G. Neugebauer *et al.*, "The infrared astronomical satellite (IRAS) mission," *Astrophys. J.*, Part 2, vol. 278, pp. L1–L6, Mar. 1984, doi: 10.1086/184209.

[49] National Aeronautics and Space Administration, "LAMBDA-Data products," 2020. Accessed: Jul. 27, 2020. [Online]. Available: https://lambda.gsfc.nasa.gov/product/cobe

[50] G. F. Smoot and K. Davidson, *Wrinkles in Time*. New York, NY, USA: William Morrow, 1994, ISBN 0-380-72044-2.

[51] Wikipedia, "Cosmic background explorer," 2020. Accessed: Jul. 27, 2020. [Online]. Available: https://en.wikipedia.org/wiki/Cosmic_Background_Explorer

[52] S. P. Boughn, E. S. Cheng, and D. T. Wilkinson, "Dipole and quadrupole anisotropy of the 2.7 k radiation," *Astrophys. J.*, vol. 243, pp. L113–L117, Feb. 1981.

[53] F. Melchiorri, B. O. Melchiorri, C. Ceccarelli, and L. Pietranera, "Fluctuations in the microwave background at intermediate angular scales," *Astrophys. J.*, vol. 250, pp. L1–L4, Nov. 1981.

[54] P. H. Siegel, "Paul l. Richards: Working at the edge - transition edge sensors and the edge of the universe," *IEEE Trans. THz Sci. Technol.*, vol. 1, no. 2, pp. 341–348, Nov. 2011.

[55] S. Hayakawa *et al.*, "Cosmological implication of a new measurement of the submillimeter background-radiation," *Publications Astron. Soc. Jpn.*, vol. 39, pp. 941–948, 1987.

[56] T. Matsumoto *et al.*, "The submillimeter spectrum of the cosmic background-radiation," *Astrophys. J.*, vol. vol. 329, no. 2, pp. 567–571, 1988.

[57] A. T. Serlemitsos, "Flight worthy infrared bolometers with high throughput and low NEP," in *Proc. SPIE, Cryogenic Optical Systems and Instruments III*, 1988, vol. 0973, pp. 314–321.

[58] National Aeronautics and Space Administration, "LAMBDA-Data products, subset FIRAS CMB temperature map," 2020. Accessed: Jul. 27, 2020. [Online]. Available: https://lambda.gsfc.nasa.gov/product/cobe/firas_cmbtm_get.cfm. DATA File Name = FIRAS_TEMPERATURE_MAP_LOWF.FITS, Delivery Date = 2003-03-01

[59] S. P. Boughn, E. S. Cheng, D. A. Cottingham, and D. J. Fixsen, "A balloon borne 19-GHz radiometer," *Rev. Sci. Instrum.*, vol. 61, no. 1, pp. 158–164, 1990.

[60] G. F. Smoot, "COBE DMR observations of early universe physics," in *Proc. AIP Conf.*, 1992, vol. 272, pp. 1591–1601. [Online]. Available: https://doi.org/10.1063/1.4341

[61] National Aeronautics and Space Administration, "LAMBDA-Data products: DMR images," 2020. Accessed: Jul. 27, 2020. [Online]. Available: https://lambda.gsfc.nasa.gov/product/cobe/cobe_images/cmb_fluctuations_big.gif

[62] G. Smoot *et al.*, "COBE differential microwave radiometers: Instrument design and implementation," *Astrophys. J.*, vol. 360, pp. 685–695, Sep. 1990.

[63] N. Jarosik *et al.*, "First year Wilkinson microwave anisotropy probe (WMAP) observations: On-orbit radiometer characterization," *Astrophys. J. Suppl. Ser.*, vol. 148, no. 1, pp. 29–37, 2003.

[64] National Aeronautics and Space Administration, "WMAP Wilkinson microwave anisotropy probe, WMAP mission," 2020. Accessed: Jul. 29, 2020. [Online]. Available: https://map.gsfc.nasa.gov/mission/

[65] M. Devlin *et al.*, "Mapping the CMB I: The first flight of the QMAP experiment," *Astrophys. J.*, vol. 509, pp. L69–L72, 1998.

[66] E. Torbet *et al.*, "A measurement of the angular power spectrum of the microwave background made from the high Chilean Andes," *Astrophys. J.*, vol. 521, pp. L79–L82, 1999.

[67] P. J. E. Peebles and J. T. Yu, "Primeval adiabatic perturbation in an expanding universe," *Astrophys. J.*, vol. 162, pp. 815–836, 1970.

[68] R. A. Sunyaev and Y. B. Zel'dovich, "Small-scale fluctuations of relic radiation," *Astrophys. Space Sci.*, vol. 7, pp. 3–19, 1970.

[69] J. R. Bond, B. J. Carr, and C. J. Hogan, "Spectrum and anisotropy of the cosmic infrared background," *Astrophys. J.*, vol. 306, pp. 428–450, 1986.

[70] J. Glanz, "Clearest picture of infant universe sees it all and questions it," *New York Times*, Sec. A, p. 1, Apr. 27, 2000.

[71] P. de Bernardis *et al.*, "A flat universe from high-resolution maps of the cosmic microwave background radiation," *Nature*, vol. 404, pp. 955–959, 2000.

[72] S. Padin *et al.*, "First intrinsic anisotropy observations with the cosmic background imager," *Astrophys. J.*, vol. 549, pp. L1–L5, 2001.

[73] S. A. Colgate, "Supernovae as a standard candle for cosmology," *Astrophys. J.*, vol. 232, pp. 404–408, 1979.

[74] A. G. Riess *et al.*, "Observational evidence from supernovae for an accelerating universe and a cosmological constant," *Astrophys. J.*, vol. 116, pp. 1009–1038, 1998.

[75] S. Perlmutter *et al.*, "The supernova cosmology project: Measurements of Ω and Λ from 42 high-redshift supernovae," *Astrophys. J.*, vol. 517, pp. 565–586, 1999.

[76] E. M. Leitch *et al.*, "Measurement of polarization with the degree angular scale interferometer," *Nature*, vol. 420, pp. 763–771, 2002.

[77] C. L. Bennett *et al.*, "Nine year Wilkinson microwave anisotropy probe (WMAP) observations: Final maps and results," *Astrophys. J. Suppl. Ser.*, vol. 208, 2013.

[78] G. Hinshaw *et al.*, "Nine year Wilkinson microwave anisotropy probe (WMAP) observations: Cosmological parameter results," *Astrophys. J. Suppl. Ser.*, vol. 208, 2013.

[79] The European Space Agency, "Planck CMB," 2020. Accessed: Jul. 29, 2020. [Online]. Available: https://www.esa.int/esearch?q=Planck+CMB

[80] N. Aghanim *et al.*, "Planck 2018 results I. Overview and the cosmological legacy of Planck," *Astronomy Astrophys.*, Oct. 2019, doi: 10.1051/0004-6361/20183388.

[81] R. A. Sunyaev and Y. B. Zel'dovich, "The observations of relic radiation as a test of the nature of X-ray radiation from the clusters of galaxies," *Comments Astrophys. Space Phys.*, vol. 4, pp. 173–178, 1972.

[82] U. Seljak, "Measuring polarization in cosmic microwave background," *Astrophys. J.*, vol. 482, pp. 6–16, 1997.

[83] M. Zaldarriaga and U. Seljak, "Gravitational lensing effect on cosmic microwave background polarization," *Phys. Rev. D*, vol. 58, 1998, Art. no. 023003.

[84] A. Kusaka *et al.*, "Results from the Atacama B-mode Search (ABS) experiment," *J. Cosmol. Astropart. Phys.*, vol. 2018, Sep. 2018, doi: 10.1088/1475-7516/2018/09/005.

[85] The Polarbear Collaboration: P. A. R. Ade *et al.*, "A measurement of the cosmic microwave background B-mode polarization power spectrum at sub-degree scales with POLARBEAR," *Astrophys. J.*, vol. 794, no. 2, pp. 22, Oct. 2014, doi: 10.1088/0004-637X/794/2/171.

[86] P. A. R. Ade *et al.*, "Constraints on primordial gravitational waves using Planck, WMAP, and new BICEP2/Keck observations through the 2015 season," *Phys. Rev. Lett.*, vol. 121, Nov. 2018, Art. no. 221301.

[87] D. Hanson *et al.*, "Detection of B-mode polarization in the cosmic microwave background with data from the south pole telescope," *Phys. Rev. Lett.*, vol. 111, 2013, Art. no. 141301.

[88] European Space Agency, "E-modes and B-modes in the CMB polarisation from SPT and Herschel data." Accessed: Sep. 9, 2020. [Online]. Available: https://sci.esa.int/web/herschel/-/52905-e-modes-and-b-modes-in-the-cmb-polarisation-from-spt-and-herschel-data

[89] M. H. Abitol *et al.*, *CMB-S4 Technology Book*, 1st ed., Office of Scientific and Technical Information (OSTI), 191 pages, 2019. [Online]. Available: https://arxiv.org/abs/1706.02464

[90] J. Mather, G. Hinshaw, and L. Page, "Cosmic microwave background," in *Planets, Stars and Stellar Systems,* T. D. Oswalt Ed. Dordrecht, Germany: Springer, 2013, ch. 13, pp. 609–684, doi: 10.1007/978-94-007-5609-0_13.

[91] P. J. E. Peebles, L. A. Page, and R. B. Partridge, Eds., *Finding the Big Bang.* Cambridge, U.K.: Cambridge Univ. Press, 2009, ISBN-13: 978-0521519823.

PETER H. SIEGEL (Life Fellow, IEEE) received the B.A. degree in astronomy from Colgate University in 1976, the M.S. degree in physics from Columbia University in 1978, and the Ph.D. degree in electrical engineering (EE) from Columbia University in 1983. He has held appointments as a Research Fellow and Engineering Staff at the NASA Goddard Institute for Space Studies, New York City, NY, USA, from 1975 to 1983; a Staff Scientist at the National Radio Astronomy Observatory, Central Development Labs, Charlottesville, VA, USA, from 1984 to 1986; a Technical Group Supervisor and a Senior Research Scientist at Jet Propulsion Laboratory (JPL), National Aeronautics and Space Administration (NASA), Pasadena, CA, USA, from 1987 to 2014; and a Faculty Associate in electrical engineering and a Senior Scientist in biology at the California Institute of Technology (Caltech), Pasadena, CA, USA, from 2002 to 2014. At JPL, he founded and led for 25 years the Submillimeter Wave Advanced Technology (SWAT) Team, a group of over 20 scientists and engineers developing THz technology for NASA's near-term and long-term space missions. This included delivering key components for four major satellite missions and leading more than 75 smaller Research and Development programs for NASA and the U.S. Department of Defense. At Caltech, he was involved in new biological and medical applications of THz, especially low-power effects on neurons and most recently millimeter-wave monitoring of blood chemistry. He has served as an IEEE Distinguished Lecturer, and the Vice-Chair and Chair of the IEEE MTTS THz Technology Committee. He is currently an Elected Member of the MTTS AdCom. Dr. Siegel has published more than 300 articles on THz components and technology and has given more than 250 invited talks on this subject throughout his career of 45 years in THz. His current appointments include the CEO of THz Global, a small Research and Development company specializing in RF bioapplications, a Senior Scientist Emeritus of biology and electrical engineering with Caltech, and a Senior Research Scientist Emeritus and a Principal Engineer with NASA Jet Propulsion Laboratory. Dr. Siegel has been recognized with 75 NASA technology awards, ten NASA team awards, the NASA Space Act Award, three individual JPL awards for technical excellence and four JPL team awards, and the IEEE MTTS Applications Award in 2018. He is honored to take up the responsibility as the Founding Editor-in-Chief of IEEE JOURNAL OF MICROWAVES, which he hopes will invigorate the microwave field. Among many other functions, he served as the Founding Editor-in-Chief for IEEE TRANSACTIONS ON TERAHERTZ SCIENCE AND TECHNOLOGY, from 2010 to 2015, and the Founder, in 2009, Chair through 2011, and elected General Secretary since 2012, of the International Society of Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), the world's largest society devoted exclusively to THz science and technology.