

REFLECTIONS ON EARLY WORK ON 'BIG BANG' COSMOLOGY

The standard model of the universe's development—the hot Big Bang—is successful in accounting for the fossil cosmic background radiation and the high, uniform cosmic abundance of helium.

Ralph A. Alpher and Robert Herman

Primordial nucleosynthesis of the lightest elements in the early universe and stellar nucleosynthesis of the heavier elements are by now both reasonably well understood. The classic paper on stellar nucleosynthesis of elements heavier than helium was published in 1957 by Margaret Burbidge, Geoffrey Burbidge, William Fowler and Fred Hoyle, and that on light-element primordial nucleosynthesis in 1967 by Robert V. Wagoner, Fowler and Hoyle.¹ The physical conditions required for primordial element-building also provide useful insights into—and constraints on—the allowable number, type and degeneracy of neutrinos, the number and properties of weakly interacting particles, the mean density of luminous matter, and the entropy per baryon, or photon-to-baryon ratio. For many years that ratio was the one “free” parameter in the canonical Big Bang model, although we, with George Gamow,² and others had long since suggested that it should not be considered free, but should be explained as a natural consequence of the physics of the very early universe.

While there are excellent current reviews on various aspects of the Big Bang cosmological model, treatises on cosmology and also a number of books for the general reader,³ we would like to give the reader a historical perspective on our early work on nucleosynthesis in the early universe. Thinking back, we could not help but be struck by the observation that contrary to what is so often presented, science does not necessarily proceed in an orderly and logical fashion.

In 1951, in a joint invited paper presented at a meeting of The American Physical Society, we discussed light-element nucleosynthesis in the early universe, the

difficulty of primordial heavy-element synthesis, and our prediction of a remnant cosmic background radiation in the universe today at a calculated temperature of 5 kelvin. There was also a discussion of the difficulty radioastronomers at the Naval Research Laboratory and at the National Bureau of Standards perceived at that time in detecting such a background. One of the participants in that 1951 session, Llewelyn H. Thomas, offered us the use of IBM's CPC (card-programmed calculator) computer facilities at the Watson Scientific Laboratory off the Columbia campus, a precursor of the IBM laboratory at Yorktown Heights. We used this computer for our earliest nucleosynthesis calculations.

In 1965 Arno Penzias and Robert Wilson⁴ reported their serendipitous observation of cosmic background radiation at about 3 K. Since then, and with subsequent measurements by many other investigators, the cosmic background radiation has become a very strong indicator of the validity of the Big Bang model, a useful “absolute frame” for considering large-scale streaming motions in the universe, and a considerable constraint in developing theories of galaxy formation because of the isotropy this radiation exhibits. (See *PHYSICS TODAY*, October 1987, page 19.)

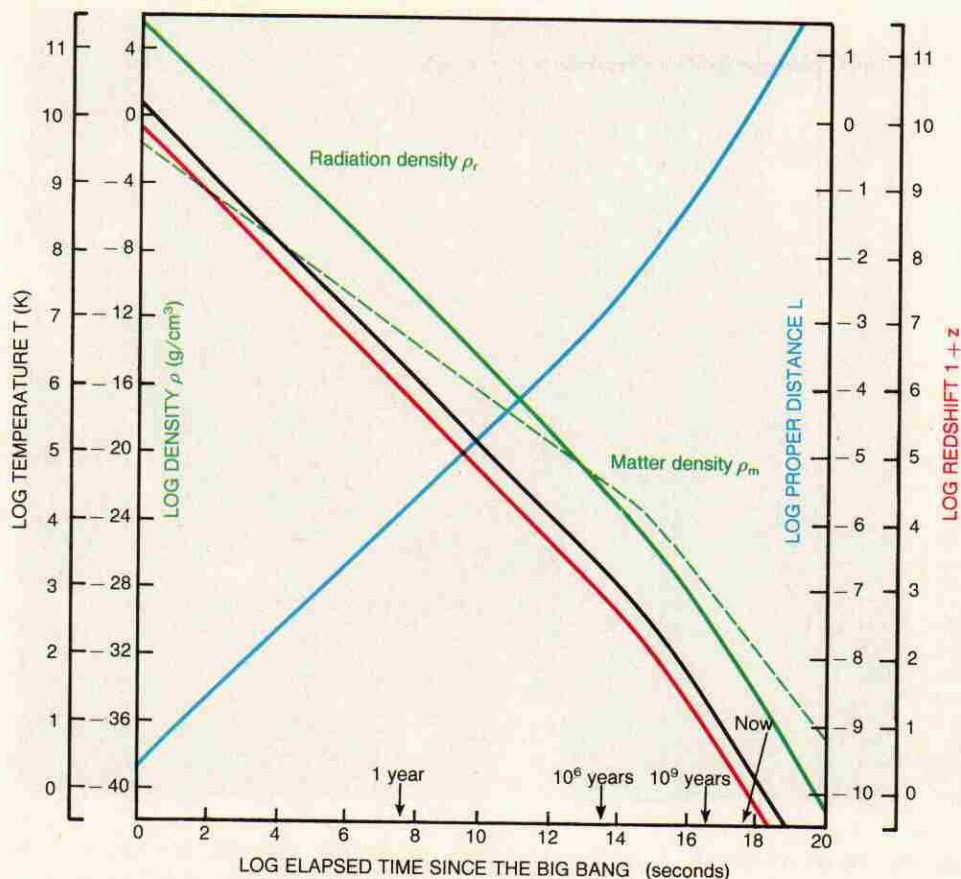
Early in the universe with George

To describe the primordial mix from which the elements were formed Alpher introduced the word “ylem.”⁵ But Hoyle was responsible for introducing “Big Bang” as a descriptor of an evolving, expanding universe. He first used this phrase in a pejorative sense during a BBC radio broadcast.⁶ The name has outlived the steady-state cosmology that Hoyle and his colleagues advocated.

We would be remiss in not acknowledging the excitement of our long collaboration with Gamow, known as Geo (“Joe”) to his friends (see the figure on page 26). Gamow was certainly one of the great scientists of this century, a man with a deep love for science and an amazing intuitive feeling for physics. In our view Gamow did not receive all the formal recognition he deserved for his many creative contributions. It is possible, but

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Cosmological parameters as a function of epoch for an open standard Big Bang model with a matter density 0.06 times the critical density, a Hubble parameter of 55 km sec⁻¹ megaparsec⁻¹ and a present background radiation at a temperature of 2.7 K. This "Divine Creation Curve" is described elsewhere by the authors.²⁰

regrettable, that Gamow's fun-loving and irrepressible approach to physics led some scientists not to take seriously his work, and perhaps our work too because of our close identification with him.

It may clarify our relationship with Gamow to describe briefly how we all came to work together. In 1944 Alpher, while a part-time graduate student pursuing evening courses at George Washington University, where Gamow was on the faculty, left the US Navy Department to join the staff of the Applied Physics Laboratory at Johns Hopkins. Gamow later became a consultant there; Herman had joined the lab several years before Alpher, after receiving his doctorate in physics at Princeton University and working for a time at the University of Pennsylvania and at the City College of New York. Herman's dissertation at Princeton was in molecular spectroscopy; he studied relativity and cosmology with H. P. Robertson, who also headed his PhD examining committee. (See the article on Robertson by Yakov Zel'dovich in *PHYSICS TODAY*, March, page 27.) During the war years, Alpher worked on ship degaussing and proximity torpedo exploders, while Herman worked on the proximity fuse for naval antiaircraft shells. Immediately after the war Alpher switched to work in supersonic aerodynamics, as well as high-altitude rocket studies of primary cosmic rays with James Van Allen; Herman meanwhile pursued fundamental spectroscopic studies related to combustion reactions.

With Gamow as his PhD adviser, Alpher began to look at primordial nucleosynthesis in 1946 as a topic for his doctoral dissertation. At that time he had finished research on and begun to write up what was to be an ill-fated dissertation dealing with the growth of adiabatic and isothermal condensations in a relativistic expanding medium. One day Gamow came into Alpher's office

waving an issue of the *Soviet Journal of Physics* he had just received; in it was published a dissertation by Evgenii Lifshitz on the same subject, and incidentally with the same results. So it was back to the drawing board for another topic.

Gamow suggested to Alpher that he follow up one of Gamow's nascent ideas, namely the possibility that the elements were synthesized in a nonequilibrium dynamical fashion in the early stages of an expanding universe. We—Alpher and Herman—were neighbors at the Johns Hopkins lab, and Herman provided a sounding board for Alpher as work on the dissertation progressed. Eventually we became collaborators, beginning an exciting and productive association that has continued for over 40 years. Our first joint paper included the prediction of the remnant cosmic background radiation.⁷ That paper, as well as a joint paper with Gamow,⁸ was published in 1948 at very nearly the same time as Alpher's dissertation.⁵ Indeed, our first nucleosynthesis calculation⁹ was published the same month as Alpher's dissertation.

What was the intellectual climate like at the time? The expansion of the universe was an accepted phenomenon, but many—including Einstein—still appeared to be more comfortable with the idea of a static cosmos. Thus the intellectual soil was fertile for the steady-state theory, which appeared to satisfy both requirements and which was the subject of active study by Hoyle, Hermann Bondi, Thomas Gold and others in England. It did not help the acceptance of an evolving, expanding cosmological model that Edwin Hubble's expansion parameter—often called the Hubble constant—as measured in the late 1940s and early 1950s gave an unacceptably short (Hubble) age for the universe: The Earth was apparently older than the universe itself! Despite this problem Gamow and, somewhat later, we tried to put physics into a nonstatic

Montage of vintage 1949 photographs of Robert Herman, George Gamow and Ralph Alpher (left to right), used in Gamow's autobiography, *My World Line* (Viking, New York, 1970). Gamow is shown emerging from a bottle of "ylem" (the primordial mix from which the elements formed). Alpher and Herman prepared the montage of Gamow and the bottle of ylem and slipped it into a collection of slides being shown by Gamow—unknown to him.



cosmological model and to explore the consequences of such an approach. We suggest several reasons for our work's not being taken seriously: There was the just-mentioned age problem; by the 1950s new values of Hubble's parameter had eliminated this. Also, some scientists had a philosophical predilection toward a steady-state universe. Finally, there was the above-mentioned view of Gamow's work and, perhaps by association, our work. Some have suggested additional sociological reasons, including these: While we did this work in the academic environment of a university laboratory, it was at a time when cosmology was not in vogue or considered important; we have never been associated with or identified with a cadre of astrophysicists or astronomers; and we spent considerable portions of our scientific careers in industry—Alpher at General Electric's Corporate Research and Development (1955–86) and Herman at General Motors Research Laboratories (1956–79)—during the years when cosmology became increasingly important, both scientifically and in the public eye.

Gamow was concerned that the model being developed would be considered too speculative for the *Astrophysical Journal*, and in particular would not be acceptable to Subrahmanyan Chandrasekhar, one of its editors. Consequently—and fortunately—the work was submitted to and readily accepted for publication in "more daring" physics journals and *Nature*. Chandrasekhar had in fact published with Louis R. Henrich in 1942 a paper in the *Astrophysical Journal* that we believe¹⁰ to have been the best attempt at an equilibrium theory of formation. Its failure pointed up the need for a nonequilibrium approach, as even Chandrasekhar and Henrich suggested.

Several parallel paths that converged at the end of 1946 stimulated the progress of the work. Consider first where Gamow's ideas stood at that time. As early as 1935 he had given a talk at Ohio State University, later published in the relatively obscure *Ohio Journal of Science*,¹¹ in which he discussed the possibility of thermo-

nuclear reactions in stellar interiors leading to the abundance distribution of the elements. He was particularly intrigued with the idea that although building the entire sequence of element abundances with reactions involving protons would require extreme temperatures, one might build up toward the heavier elements by neutron-capture reactions, which were at that time newly described by Enrico Fermi. Gamow's ideas presaged the so-called s-process of stellar nucleosynthesis.¹

By 1942 Gamow was receiving added stimulation from several developments: the emerging picture of stellar energy resulting from the proton-proton and carbon-nitrogen cycles, as developed by Hans Bethe, Carl Friedrich von Weizsäcker, Charles L. Critchfield, Edward Teller, Robert d'Escourt Atkinson, Fritz G. Houtermans and Gamow himself, among others; the increasing confidence that the relative abundance distribution of the elements was uniform throughout the cosmos; and, most particularly, the failure of the multitude of so-called equilibrium theories to explain the abundance distribution.¹⁰ As a consequence, in 1942 Gamow gave a talk to the Washington Academy of Sciences on another approach.¹² He proposed that the abundance distribution might be the result of a nonequilibrium breaking-up process, in which an original superdense object composed of nuclear matter would fragment not unlike the primeval atom first proposed by Georges Lemaître in 1931, heavy elements would be built up by neutron-capture reactions, and fission fragments would cycle back as the limit of nuclear stability past uranium was exceeded, all in the context of expansion in the early stages of the universe.

In a 1946 publication Gamow proposed yet another approach.¹³ In this paper he actually estimated, based on the Robertson-Walker metric, the early rate of expansion of a matter-dominated Friedmann-Lemaître cosmological model. He concluded, first, that at high densities of matter the rate of expansion would have been far too rapid to permit an equilibrium distribution to be established, and second, that if neutron-capture reactions were primar-

ily responsible for establishing the abundance distribution, which would require that free neutrons were plentiful in the early universe, then the time available for thermonuclear reactions would have been short compared with the neutron halflife. He hypothesized a comparatively cold cloud of neutrons that somehow coagulated into heavier complexes, which in turn underwent beta decay, moving into the nuclear stability region and thereby building up the heavier elements. The high abundance of hydrogen was taken to be the result of competition for neutrons between the coagulation process and neutron beta decay.

Elementary cooking

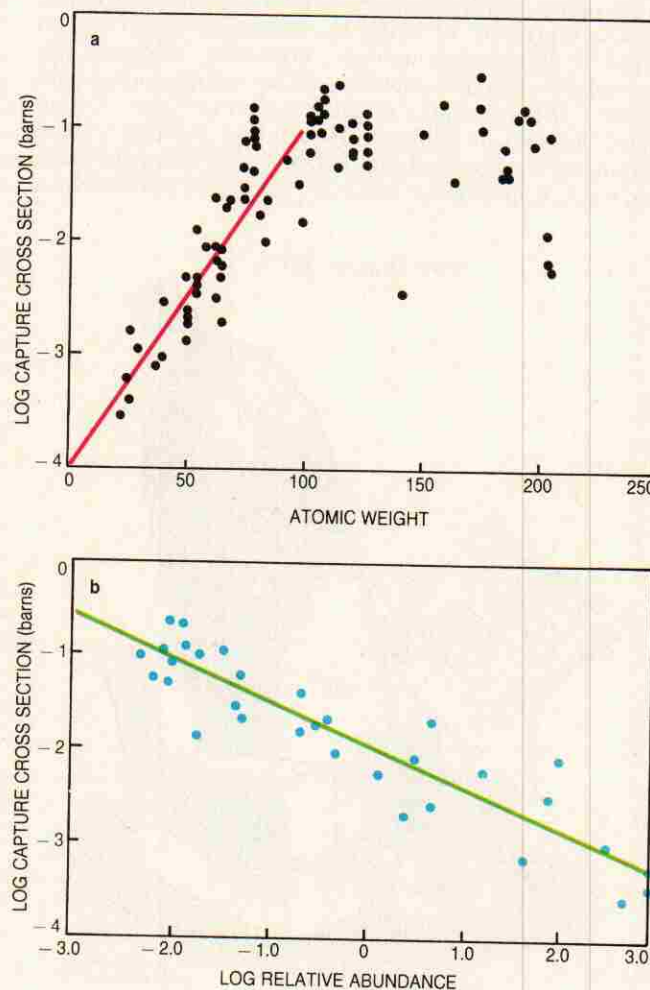
Consider now what actually stimulated all of these ideas, namely, the notion that the relative abundance distribution of the elements was universal. It began around 1914 with statements in the literature by William D. Harkins and Giuseppe Oddo that the abundance distribution of the elements reflected their nuclear rather than their chemical properties.¹⁰ In the 1930s Victor M. Goldschmidt published a cosmic abundance distribution based on the then well-established idea that stars were all made of the same stuff, an astrophysical conclusion to which Cecilia Payne and Henry Norris Russell made prominent contributions (see the article by Leo Goldberg on page 38), together with work on the composition of meteorites, the Earth's crust and interstellar matter. Shortly after World War II, detailed corrections were made in the abundance distribution data by Harrison Brown, Hans Suess, Harold Urey and others, so Alpher and Gamow had a reasonably reliable abundance distribution to work with. The data points in the figure on page 29 are Brown's revisions of Goldschmidt's data. This plot formed the basis of the papers by Gamow and by us that dealt with primordial nucleosynthesis. Note the low abundances of lithium, beryllium and boron as well as the pronounced peak at iron. (The superimposed calculated curves are discussed below.)

The development of Gamow's ideas in 1946 was difficult and problematic. There was a paucity of thermonuclear reaction cross section data; those that existed had not yet been declassified from wartime, and were not available to us. In late 1946 work by Donald J. Hughes (Brookhaven) constituted a breakthrough for ideas on cosmological nucleosynthesis. He had surveyed neutron-capture cross sections at 1 MeV for a large number of elements in an attempt to determine the suitability of various materials for reactor construction. What was exciting about Hughes's results was that the cross sections varied inversely with the relative abundance data, as shown in the figure at right. Moreover, Hughes's data, as well as other, fragmentary data that could be related to his work (also shown in the figure), exhibited very low capture cross sections for "magic number" nuclei, whose abundances were elevated relative to those of neighboring nuclei. This further suggested a strong inverse relationship between abundance and neutron-capture cross section.

Alpher used Hughes's results in his dissertation calculations.⁵ Alpher assumed that at an appropriately early time the universe consisted of a gas of neutrons. As protons became available from neutron decay, neutron-capture reactions commenced to build up the abundance distribution of the elements. In this first attempted model of primordial nucleosynthesis, which did not take the expansion into account explicitly, the neutron-capture cross sections were represented as showing a simple exponential increase up to atomic weight 100, with a constant value thereafter for the heavier elements. The

nuclear reactions were assumed to begin when the universal temperature had fallen below the binding energy of the deuteron, about 0.1 MeV; the cross sections were corrected from 1 MeV to 0.1 MeV by assuming they varied as $1/E$. It was further assumed that nucleosynthesis was completed in a time short compared both with the universal decrease in temperature resulting from expansion and also with the radioactive decay of neutrons.

This first, very simplified static calculation, described in what has become known as the $\alpha\beta\gamma$ (Alpher-Bethe-Gamow) theory,¹⁴ did not explicitly consider the radiation domination of the universe at early times (although this was discussed in detail in Alpher's dissertation⁵) and led to what seemed at first glance to be a very high value of the density of matter during nucleosynthesis. Simplified as this approach may have been, it nevertheless mapped the general nature of the abundance distribution, which had not been done before, suggested a rationale for the relatively high abundance of the light elements, and appeared to require an early universe that was both hot and dense. These results confirmed Gamow's 1946 ideas, and also gave the first intimation of a hot, dense origin for the universe. The results are shown in the figure on page 29, superimposed on the basic cosmic abundance data referred to earlier. Curves I, II and III represent different



Neutron-capture cross sections at 1 MeV vs atomic weight (a) and vs relative abundance (b). These 1946 data obtained by Donald J. Hughes were the basis for early nucleosynthesis calculations based on the neutron-capture sequence. (Adapted from ref. 5.)

values of the product of the starting neutron concentration and the assumed duration of nucleosynthesis. For curve II, this product is $8 \times 10^{17} \text{ sec/cm}^3$; for curve I it is twice this value; and for curve III, one-third. The "steady state" curve is the result achieved by allowing the process to run indefinitely. Even before the appearance of this paper, as we discuss below, we were occupied with improved calculations that took the universal expansion into account explicitly.

There were several amusing consequences of the $\alpha\beta\gamma$ paper.¹⁴ One, which may already be well known to many readers, concerned the addition by Gamow of Bethe's name as a coauthor "*in absentia*" (with at least Bethe's implicit approval). The editor of *Physical Review* chose to remove "*in absentia*," and Bethe lists the paper in his *curriculum vitae*. Bethe has told us, "I felt at the time that it was rather a nice joke, and that the paper had a chance to be correct, so that I did not mind my name being added to it." Moreover, at Gamow's invitation Bethe sat on Alpher's dissertation defense committee. (Despite Gamow's later entreaties Herman did not change his name to Delter.) Watson Davis of *Science Service* (now *Science News*) learned of Alpher's dissertation defense from a mailing by George Washington University to local alumni, and wrote a short news summary that was picked up by a

number of newspapers nationwide. This generated an unusually large audience for the public defense. The news item also prompted the cartoonist for *The Washington Post* who signs his work "Herblock" to publish a cartoon (reproduced on this page) that derived from a result in Alpher's dissertation, namely, that the period of nucleosynthesis lasted some 300 seconds.

In our developments beyond the $\alpha\beta\gamma$ paper, it was immediately apparent to us that sequential build-up of the elements was not adequate; that one would have to look in detail at all of the thermonuclear reactions among light nuclei, and not just at a smoothed neutron-capture cross section function; and that there would be a major problem resulting from the absence of stable nuclei at masses 5 and 8. Another problem, already mentioned, was the short age for the cosmological model given the then-current value of the Hubble constant. Furthermore, one had to consider a cosmological model with a mixture of matter and radiation as the working fluid, and with radiation dominating the behavior of the model at early times. It was also evident, as assumed in the $\alpha\beta\gamma$ paper, that sequential build-up could not have been significant until the temperature had fallen below a value equivalent to the binding energy of the deuteron, when photodisintegration would have become unimportant.

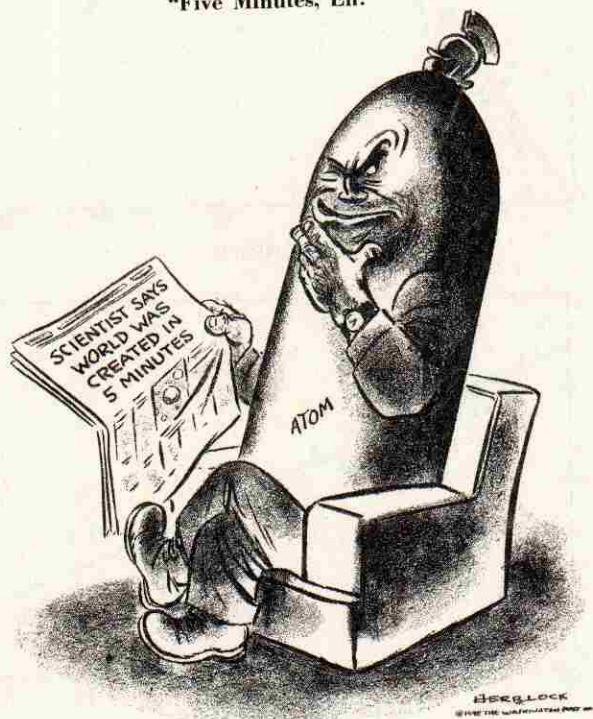
Following up these points in one of his characteristically insightful—but "quick and dirty"—calculations, Gamow tried to get at the conditions in the early universe and at the same time see what he could do about the tantalizing problem of the formation of galaxies. Two publications^{15,16} by Gamow in 1948 covered these ideas in some detail, and, incidentally, the second of these led us to our prediction of the remnant blackbody radiation in the universe.

Prediction of fossil radiation

Because many have misinterpreted what the $\alpha\beta\gamma$ paper stated, we emphasize that it did not consider any current consequences of the universe's being hot and radiation dominated at early times. We took the conceptual and extrapolative step to a current cosmic background radiation later in 1948 when we calculated the approximately 5-K background.⁷ Moreover, contrary to statements by David Wilkinson and James Peebles,¹⁷ Gamow made no reference in his own 1948 *Nature* paper¹⁶ to a 10-K background, nor, in our 1948 *Nature* paper,⁷ had we "repeated Gamow's calculation with greater accuracy, using a computer," in the context of the background blackbody radiation. We did redo Gamow's calculations with respect to galaxy formation, but the prediction and calculation of a remnant blackbody cosmic background radiation of 5 K had nothing to do with the subject of Gamow's paper.

Gamow supposed that the time dependences of the temperature and of the density of matter at early times were given by an approximation of the relativistic description of an expanding model (see the box on page 32). He further supposed that one could start with neutrons only and use simple rate equations for the neutron and proton concentrations, with neutrons being lost to beta decay and appearing as protons, and with

"Five Minutes, Eh?"



Cartoon published in 1948 in *The Washington Post* was inspired by a statement in Alpher's dissertation to the effect that the period of nucleosynthesis in the early universe lasted about 5 minutes.

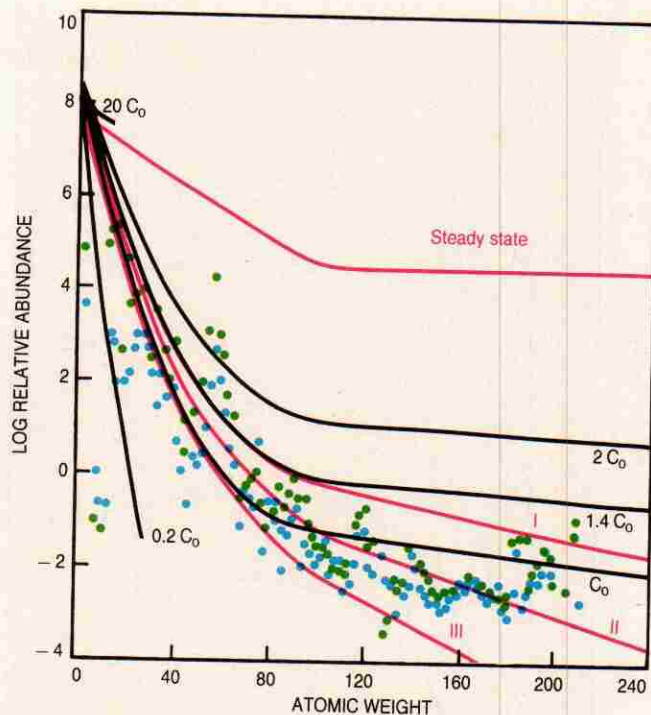
neutrons and protons being used up in forming deuterons. He then used a theoretical $n(p,\gamma)d$ reaction cross section given by Bethe¹⁸ and integrated the rate equations subject to the constraint that the final concentration of protons be one-half. The free parameter in his calculation was the density of matter, ρ_0 , at a particular early epoch, say at 1 second after the Big Bang. Gamow's calculation gave a ρ_0 value of approximately $7 \times 10^{-3} \text{ g/cm}^3$, which was consistent with the primordial density of matter calculated in the $\alpha\beta\gamma$ paper and our later calculations. He then used these quantities together with Jeans's gravitational instability criterion to derive a typically interesting Gamowian relation between the diameter and mass of galaxies on the one hand and the binding energy of the deuteron on the other. He did suggest that galaxies might have formed at the epoch when the densities of matter and radiation were equal—a "crossover," or "decoupling," time (decoupling because at this time the universe changed from being opaque to being transparent to radiation), a time between the control of the expansion by radiation earlier and by matter later. His numerical estimates of the consequent matter and radiation densities up to crossover, as well as the time to crossover from the Big Bang, were substantially incorrect because he carried the early-time approximations for the temporal behavior of matter and radiation too far.

During the summer of 1948 Gamow had sent us a copy of the manuscript dealing with this calculation, which he had already submitted to *Nature*. We pointed out the errors in the manuscript in a telegram we sent to Gamow at Los Alamos, where he was spending the summer. However, Gamow felt it was too late for him to make the needed corrections, and he urged us to submit a paper to *Nature* with these comments. Gamow advised *Nature* that a paper by us was coming and asked that it be published as soon as possible after his paper. It was in the course of these considerations that we integrated the full relativistic equations for the expansion, in the process not only finding a more reasonable crossover time but also realizing that we were in a position to examine the time dependence of all the relevant physical variables over the entire evolution of the universe. In particular we were able for the first time to predict the existence of the blackbody cosmic background radiation and to calculate its density and temperature in the present universe. The calculation (see the box on page 32), based in a relatively simple way on the then-known values of pertinent parameters, yielded a present blackbody cosmic background radiation at a temperature of 5 K. We gave this result in our 1948 *Nature* paper,⁷ and discussed it in considerable detail in later publications.^{10,19,20}

Our 1948 calculation as well as our subsequent calculations depended entirely on the simple relation between the densities of matter and radiation that must hold during the expansion if there is no interconversion of matter and radiation (see box), namely,

$$\rho_r \rho_m^{-4/3} = \text{constant}$$

If one knows the density pair (ρ_r, ρ_m) at any one epoch, then the relation defines possible values for the pair at any

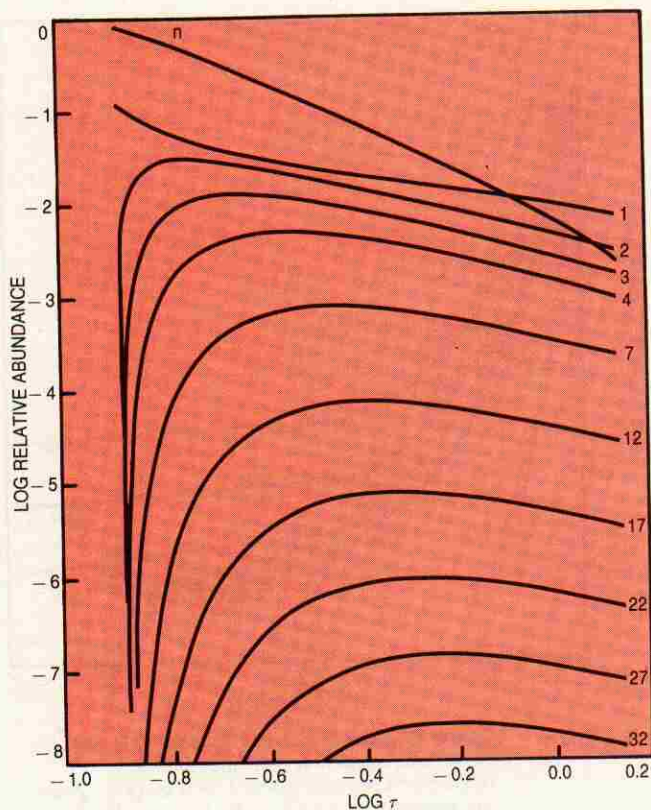


Cosmic abundance data as compiled by Harrison Brown and used in early nucleosynthesis calculations are represented here by dots: green for even atomic weight and blue for odd. The red curves marked I, II and III, adapted from a paper by Alpher,⁵ represent various starting conditions for a calculation based on the premises of Alpher and Gamow in their " $\alpha\beta\gamma$ " paper. The black curves, calculated in 1951 by Alpher and Herman,¹⁹ represent final values from the figure on page 30. The best fit is the curve marked C_0 , where C_0 stands for a matter density of $1.5 \times 10^{-3} \text{ g/cm}^3$ at 1 second.

other epoch; if three of the densities are known, the fourth can be determined. In the first 1948 calculation, we used the following data: a matter density as required for nucleosynthesis of approximately 10^{-6} g/cm^3 , and a radiation density calculated from the early-time approximation (see box) of approximately 1 g/cm^3 , each at about 640 seconds into the expansion; the present mean density of matter in the universe, as given by Hubble, was thought in 1948 to be approximately 10^{-30} g/cm^3 . In the density-pair relation above, only the present radiation density was unknown, and the calculated temperature for a blackbody cosmic background radiation was found to be approximately 5 K.

It is interesting to consider how often we published similar calculations. The original prediction⁷ of 5 K was in 1948, approximately six months after the $\alpha\beta\gamma$ paper; the next three papers were published at roughly yearly intervals after the $\alpha\beta\gamma$ paper.^{10,19} The last calculation, in 1951, was in a way unfortunate, because in the interim a new value for the universal mean density had become current (it was quickly revealed to be in error) and this led to an estimate of a background temperature of 28 K. Scholarly research being what it was—and still is, unfortunately—this particular result has not infrequently been quoted as though it were a failure of the model or of our work, rather than being dependent on what scientists at the time considered reasonable cosmological parameters.

The year 1951 was not a great year for advocates of the Big Bang model. The same data that gave an approximately 28-K background temperature also continued to



Early nucleosynthesis calculations made in 1951 by Alpher and Herman led to these curves. The calculations were based on a neutron-capture reaction sequence including neutron decay and the universal expansion.¹⁹ The time scale is in units of the neutron decay constant. The numbers at right are atomic weights of representative nuclear species. The curve marked *n* shows the neutron concentration.

give a very short age for the model. This provided much encouragement to devotees of the steady-state model, and despite their not yet having found in their model a source for the cosmic abundance of helium, as well as not yet having a detailed explanation of the formation of the rest of the elements, the steady-state model was in its ascendancy. It was not until 1964 that Hoyle and Roger J. Tayler formally recognized the formation of helium as an insuperable problem for the steady-state theory,²¹ although by then the formation of the heavier elements in stellar interiors was in reasonably good shape.¹

More or less elementary cooking

Subsequent to the $\alpha\beta\gamma$ paper there were a number of improved calculations of primordial nucleosynthesis based on neutron-capture cross sections. As an example, J. Samuel Smart considered the formation of shielded isobars and the even-odd atomic weight effect on abundances.²² In 1951 we again considered the straightforward neutron-capture sequence.¹⁹ We used the smoothed neutron-capture cross sections in rate equations that explicitly included neutron decay and the universal expansion. Preliminary calculations were carried out on a MADDIDA (an early magnetic drum storage digital computer made by North American Aviation) and final results were obtained on the SEAC (the first large digital computer resident at the National Bureau of Standards, used first to analyze 1950 census data). The figure on this page shows the evolution with τ (where $\tau = \lambda t$ and λ is the neutron decay

constant) of relative abundances for selected atomic weights. After $\tau = 0.13$ the reactions die out and the curves become parallel as the remaining neutrons decay and the mix of nuclei dilutes and cools in the expansion. The abundance is relatively high at the atomic weight of helium. In the figure on page 29 the final relative abundance values are plotted against atomic weight and compared with the cosmic abundance distribution. The best-fitting curve (marked C_0) was obtained with a matter density chosen to be approximately 1.5×10^{-3} g/cm³ at 1 second into the expansion, or roughly 9×10^{-4} g/cm³ at $\tau = 0.13$ in the figure on this page.

The relative abundances calculated with smoothed neutron-capture cross sections are of interest, but it was recognized that as soon as detailed thermonuclear reaction rates became available, particularly for the light elements, they should be explored in this context. As a result of attending a colloquium by Alpher in late 1948, Fermi, in collaboration with Anthony Turkevich, collected published values (or made new estimates) of cross sections for 28 thermonuclear reactions among nuclei up to atomic weight 7. Fermi and Turkevich used these cross sections together with the early-time approximations for the cosmological model to solve the rate equations among these 28 reactions, subject to the conditions that the reactions began at about 300 seconds into the expansion, when the temperature had fallen to about 0.07 MeV and photodissociation reactions would no longer be important; that the neutrons and protons were initially in the ratio 7:3, as would result from starting with neutrons only at 1 second; and, finally, that the neutron decay constant was 10^{-3} sec⁻¹. We reported¹⁰ their results in 1950 (see the figure on page 31). Again note the high abundance of primordial helium. No way was found at that time to continue a building-up process past atomic weights 5 and 8. Suggestions for bridging the atomic weight gaps at 5 and 8 were made by Fermi, Eugene Wigner, Chushiro Hayashi and others over the next few years, but none resolved the difficulty at the time. Several researchers²³ have more recently considered the role of density or compositional inhomogeneities in the early universe in providing a mechanism for bridging these gaps and allowing primordial nucleosynthesis of the heavier elements.

An additional concern in the early work was the lack of detailed knowledge of the initial conditions for the period of nucleosynthesis. In late 1950 Hayashi²⁴ proposed that instead of starting with an ylem of pure neutrons, one should calculate the initial relative concentrations of neutrons and protons for nucleosynthesis by considering the outcome of reactions among elementary particles and radiation starting at a temperature in the expansion just less than that equivalent to the meson rest mass. He performed such calculations and derived an abundance ratio of neutrons to protons that was too small to be useful as a starting condition if the simple neutron-capture sequence was to represent nucleosynthesis. Thereafter we, together with our Applied Physics Lab colleague James W. Follin Jr, undertook²⁵ the most detailed calculations in the spirit of Hayashi's approach that we could manage under the constraints of the state of physics in 1952. The major differences between our calculations with Follin and those of Hayashi were that we used relativistic quantum statistics appropriate to the prevailing conditions and that the then-current value for the neutron decay constant was significantly different from Hayashi's value.

The calculations were begun at a temperature of 100 MeV, or approximately 10^{12} K, with the assumption that thermodynamic equilibrium prevailed for all species

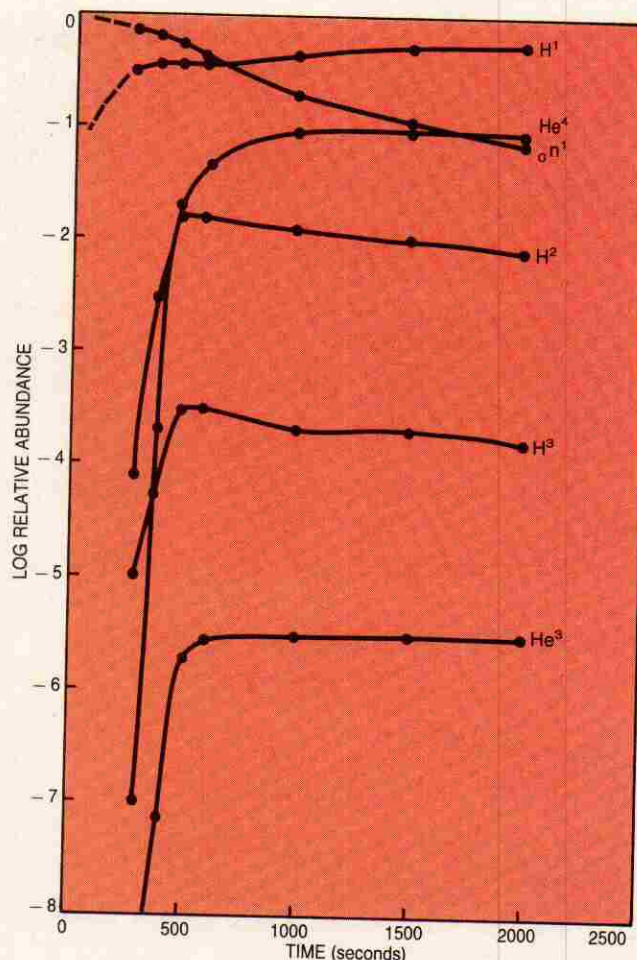
except baryons and antibaryons, for which a temperature of 100 MeV was too low for interconversion. The predominance of baryons over antibaryons, we assumed, had been established prior to the time when the temperature dropped to 100 MeV, by physical processes then unknown and still problematical. The universe had cooled to about 100 MeV by approximately 6×10^{-5} sec. Using the temperature-time relation appropriate to early times in the expansion, we calculated with Follin the contributions of baryons, leptons and radiation to the total mass density, which controlled the expansion. The two Dirac neutrino cases we considered, namely, distinguishable and indistinguishable neutrinos, made a significant difference in the ratio of the total density to the radiation density. While the neutron-proton ratio we obtained was indeed different from that obtained by Hayashi, it was not appropriate for a successful neutron-capture sequence for all the elements. We continued collaborating with Follin until 1960, using our earlier joint work as a basis for further consideration of the formation of the light elements, but the results were reported only in a series of contributed papers at American Physical Society meetings.²⁶ There seemed to be little interest in the results at the time. In one additional application of the results we obtained with Follin, we showed that the baryon-antibaryon asymmetry in the universe could not be explained as a residue of a statistical fluctuation from the early time when the baryon concentration was of the same order as the photon concentration.²⁷

The figure on page 33 reproduces the timetable from the Alpher-Follin-Herman paper, which was prepared to track events in the expanding universe model.²⁵ Note the decoupling of neutrinos at about 10 MeV; the neutrino gas would then continue to expand adiabatically to the present. With the methodology of the paper and the knowledge about neutrinos at the time of its preparation, one would expect a background of neutrinos today at a temperature of about 2 K, given a present blackbody cosmic background radiation at 2.7 K. Similar calculations in the paper suggested a residual background today of gravitons, if indeed they exist, with a temperature of about 1.2 K.

Richard A. Matzner²⁸ found in 1968 an algebraic error in the Alpher-Follin-Herman paper that affected the graviton decoupling temperature we used. He recalculated the temperature of any present background gravitons to be about 1.6 K, while Steven Weinberg³ has estimated about 1 K for this quantity. These numbers are most interesting in the context of recent work²⁹ by Lloyd A. Rawley, Joseph H. Taylor, Michael M. Davis and David W. Allan, who estimated upper limits on the present density of gravitational radiation. Their results, based on studies of the stability of the "clock rate" of the millisecond pulsar PSR 1937 + 21 over a four-year period, enabled them to set an upper limit of about 1.7×10^{-34} g/cm³ for a frequency of approximately 0.8 cycle/year and an upper limit of about 7×10^{-36} g/cm³ for a frequency of approximately 0.23 cycle/year. Is it not interesting that if one assumes the number density for the massless residual gravitons to be given by the Planck distribution, 1 K corresponds to a graviton density of about 3×10^{-36} g/cm³, while 1.6 K corresponds to a graviton density of about 2×10^{-35} g/cm³?

Between prediction and discovery

In 1975 we reviewed our work on the Big Bang model and the prediction of the cosmic background radiation when we received an award for the prediction.²⁰ By that time the values of the relevant cosmological parameters had been improved. In particular we used in 1975 a present matter density of 3.4×10^{-31} g/cm³, a value consistent



Light-element abundances vs time based on 28 reactions up to lithium and beryllium by Enrico Fermi and Anthony Turkevich, as reported by Alpher and Herman.¹⁰ The expansion of the universe was not taken into account.

with the work³⁰ of J. Richard Gott, James E. Gunn, David N. Schramm and Beatrice M. Tinsley but still well below the closure density for a Hubble parameter of 55 km sec⁻¹ megaparsec⁻¹; a matter density at 1 second into the expansion of 6.9×10^{-2} g/cm³, obtained by Wagoner in his detailed study of light-element nucleosynthesis³¹; and a radiation density of approximately 4.5×10^{-5} g/cm³ at 1 second from the early-time approximation (see the box on page 32). These values yield 2.7 K for the present cosmic background radiation temperature. We show in the figure on page 25 a plot of the densities, temperatures, proper distances and redshifts for this particular model. Gamow called such plots "Divine Creation Curves" and used one on his personal letterhead for a considerable period in his later years. Clearly some concepts will have to give way if the assumed present matter density has to be corrected upward by a factor of 10 or more because of the presence of dark matter, to meet the closure requirement of inflationary models. But these considerations are beyond the purview of this particular discussion.

There were some curious aspects to our interactions with Gamow on the specific question of the background radiation. In 1948 and 1949 he argued with us personally and in correspondence that even if the concept of a remnant blackbody cosmic background radiation was real, it was not useful because of the presence of starlight at the Earth at about the same energy density. Despite this, there is not

The Standard Model: Hot Big Bang Cosmology

For a universe containing an ideal fluid of matter and radiation that are not interconverting, the Friedmann-Lemaître nonstatic solution of Einstein's field equations with a zero cosmological constant and the Robertson-Walker metric leads to the following relativistic energy equation (expressing the time rate of change of the proper distance ℓ):

$$\frac{d\ell}{dt} = \pm \left[\left(\frac{8\pi G}{3} \right) (\rho_m + \rho_r) \ell^2 - \frac{c^2 \ell_0^2}{R_0^2} \right]^{1/2}$$

where the positive sign indicates expansion, ρ_m and ρ_r are the densities of matter and radiation, respectively, c is the velocity of light, G the gravitational constant, ℓ_0 a unit proper distance and R_0 the radius of curvature. (All units are cgs.) Conservation of matter requires

$$\rho_m \ell^3 = \text{constant}$$

while requiring the adiabatic expansion of radiation leads to

$$\rho_r \ell^4 = \text{constant}$$

If radiation dominates at early times in the expansion, then

$$\rho_r \gg \rho_m$$

and $c^2 \ell_0^2 / R_0^2$ is small, so that one can write

$$\rho_r = \frac{4.5 \times 10^5}{\ell^2}$$

and consequently

$$T = \frac{1.5 \times 10^{10}}{\ell^{1/2}} \text{ kelvin}$$

where the coefficients in ρ_r and T contain only universal constants.

The energy equation can be integrated to yield the age of the expansion as a function of the other variables, namely,

$$t = K_1 + K_2^{-1} (\gamma \rho'_r + \gamma \rho'_m L + K_2 L^2)^{1/2} - \left(\frac{\gamma \rho'_m}{2K_2^{3/2}} \right) \ln \left[(\gamma \rho'_r + \gamma \rho'_m L + K_2 L^2)^{1/2} + K_2^{1/2} L + \frac{\gamma \rho'_m}{2K_2^{1/2}} \right]$$

where

$$K_1 = \left(\frac{\gamma \rho'_m}{2K_2^{3/2}} \right) \ln \left[(\gamma \rho'_r)^{1/2} + \frac{\gamma \rho'_m}{2K_2^{1/2}} \right] - \left(\frac{\gamma \rho'_r}{K_2} \right)^{1/2}$$

$$\gamma = 8\pi G/3$$

$$K_2 = c^2 / |R_0^2|$$

The quantity $L = \ell / \ell_0$ is a dimensionless proper distance, with ℓ_0 chosen so that $L = 1$ now; and ρ'_m and ρ'_r are the densities of matter and radiation when $L = 1$, and are not to be confused with the running variables. Note that in models of this type energy is not conserved. To evaluate the constant of integration, the parameters R_0 and ℓ_0 must be specified.

This expression for the time since the Big Bang can be simplified if one wants to calculate the age of the present epoch, which is matter dominated. Then with the critical total density (the density for closure of the universe) given by

$$\rho_c = \frac{3H_0^2}{8\pi G}$$

where H_0 is the present value of the Hubble parameter in sec^{-1} , one can write

$$\Omega = \frac{\rho'_r + \rho'_m}{\rho_c} \approx \frac{\rho'_m}{\rho_c}$$

It can be shown that the present age of the Big Bang, t_0 (in units of H_0^{-1}), can be written in terms of the Hubble parameter as follows:

$$H_0 t_0 = -\frac{1}{\Omega - 1} + \frac{\Omega}{2(\Omega - 1)^{3/2}} \cos^{-1} \left(\frac{2 - \Omega}{\Omega} \right), \quad \Omega > 1$$

$$H_0 t_0 = 2/3, \quad \Omega = 1$$

$$H_0 t_0 = \frac{1}{1 - \Omega} - \frac{\Omega}{2(1 - \Omega)^{3/2}} \cosh^{-1} \left(\frac{2 - \Omega}{\Omega} \right), \quad \Omega < 1$$

Details of these expressions for the age are given in *Gravitation and Cosmology* by Steven Weinberg.³

the slightest hint in Gamow's August 1950 PHYSICS TODAY article (page 16) or in our correspondence with him of how his quoted 3-K value came about. He was of course fully aware of our calculations at the time, and may have "rounded off" in his own inimitable way. Three years later in an article in a Danish journal³² Gamow estimated a 7-K background temperature by means of a strange linear extrapolation of matter and radiation densities in the expansion, despite the availability to him of our approach. And three years after that, in 1956, he persisted with yet another arcane calculation,³² obtaining 6 K. We became aware of these papers of Gamow only after they were published; we chose not to publish our disagreement with his approaches to estimating a temperature for the cosmic background radiation. That Gamow made no reference to our earlier calculations in any of these three papers has made for considerable confusion in the literature and added to the problem of correct attribution by later workers to our original calculations.

By 1956 discussions of the background radiation were to be found in four papers by Alpher and Herman and three papers by Gamow, all in such accessible journals as *Nature*, *Physical Review*, *Reviews of Modern Physics*, *PHYSICS TODAY* and *Vistas in Astronomy*. In addition, in 1964 Andrei G. Doroshkevich and Igor D. Novikov discussed a cosmic background radiation in a Soviet journal.³³ Curiously, this last paper, which was submitted

for publication by Zel'dovich, referred to a 1-10-K range for such radiation, attributing the result to a 1949 paper by Gamow³⁴ in which he in fact had not alluded to the possibility of such radiation.

Discovery of cosmic background radiation

Penzias and Wilson reported their observation of a background radiation at 7.3 cm in 1965 without interpreting it, referring instead to an explanation given in an accompanying paper by the Princeton group of Robert Dicke, Peebles, Peter Roll and Wilkinson.⁴ The latter paper interpreted the radiation as remnant background from what they called the "primeval fireball"; this identification was no casual matter, since Dicke and his colleagues at Princeton at that time had nearly completed setting up a radiometer to look for a background radiation reflecting a prior "big crunch" in a cyclic universe.

There is a brief historical discussion of these matters, including our own considerably earlier prediction, in the December 1978 PHYSICS TODAY news story (page 17) on the awarding of the Nobel Prize to Penzias and Wilson. We cannot help but note that the Princeton group made no reference in 1965, nor for some years thereafter, to the prior eight publications on the cosmic background radiation in the literature. On the other hand, The American Physical Society issued a news release in January 1949 on the occasion of a talk by us at its annual meeting. This re-

lease gave the remnant cosmic background radiation we had predicted as -268°C . Some newspaper science writers around the country included this prediction in their articles. We note that the Princeton group, beginning in 1968, made some attempts to correct their collective oversight. Nevertheless, many in the scientific community as well as in the media still appear to be unaware of the history.

The observation of a cosmic background radiation, which is widely acknowledged as among the most important cosmological findings of modern times, stimulated a veritable explosion of activity in the scientific community, both on theory and on observation, as well as an enormous interest in the public domain. Some of the theoretical work for several years thereafter plowed ground already thoroughly worked over. For example, there were a number of contributions in *Nature* working out details of a matter-radiation universe that had long since been well documented. One cannot help but wonder again about the efficiency of the scientific enterprise.

In a way, most interesting of all are the publications in 1941 by Walter S. Adams reporting observations of interstellar CN absorption toward ζ Ophiuchi and by Andrew McKellar interpreting these observations as indicating an excitation temperature of 2.3 K at a wavelength of 2.64 mm, with no obvious source of excitation.³⁵ The result is the more interesting not only because it was overlooked but also because it lay close to the blackbody peak, while the ground-based measurements of the cosmic background radiation were all at longer wavelengths. This approach has now given one of the best measures of the cosmic background radiation temperature. (See the news story on page 17.)

Beyond the early universe

Some brief remarks seem to be in order on the highlights of developments subsequent to our early work on primordial nucleosynthesis and our prediction of a background radiation. Again, we caution that this is not intended to be a comprehensive review article.

Presentations of the modern view of light-element production by primordial nucleosynthesis are widely available in the literature. Interestingly, Wagoner³¹ and others have used the methodology of the 1953 Alpher-Follin-Herman paper.²⁵ The compliment Weinberg³ paid us in referring to our joint paper as "the first thoroughly modern treatment of the early universe" and in commending the authors on being the first to take the Big Bang model seriously is much appreciated. It may yet prove possible to go beyond the light elements with primordial nucleosynthesis. Hayashi and Minoru Nishida invoked higher densities to propose an element-building synthesis chain up to neon. Much more recently James Applegate, Craig Hogan and Robert Scherrer²³ suggested that early inhomogeneities in neutron and proton concentrations could be invoked to bridge the gaps at atomic weights 5 and 8.

The Alpher-Follin-Herman paper²⁵ pushed the time frontier of the Big Bang model back to a few microseconds; this is still a very long time compared with the 10^{-43} -second horizon of the Planck time being invoked in contemporary theoretical work on the early universe. It is fascinating to consider how this theoretical work is addressing some of the conceptual problems of the canonical Big Bang model, such as the origin of the high entropy per baryon, baryon-antibaryon asymmetry and the horizon problem. (See the article by Andrei Linde in *PHYSICS TODAY*, September 1987, page 61.)

Observational confirmation of the existence of the cosmic background radiation was a great thrill for us. We

TABLE IV. Timetable of events in the early epochs of the expanding universe.

| Temperature (MeV) | Remarks | |
|---|---|------------------------------|
| | Neutrino = antineutrino | Neutrino \neq antineutrino |
| > 100 | Region of doubtful validity of the field equations where ρ_{γ} exceeds nuclear density. | |
| ~ 100 | Thermodynamic equilibrium prevails. $\rho_{\gamma} \cong 1.2 \times 10^{13} \text{ g/cm}^3$ Same as for $\nu = \bar{\nu}^*$ except $\rho_{\mu} = (7/4)\rho_{\gamma}, \rho_{\pi} = (3/2)\rho_{\gamma}$ $\rho_{\nu} = (7/4)\rho_{\gamma}$ $\rho_{\nu} = (7/8)\rho_{\gamma}, \rho_{\pi} = (7/4)\rho_{\gamma}$ $t \cong 5.9 \times 10^{-5} \text{ sec}$ $t \cong 6.3 \times 10^{-6} \text{ sec}$ | |
| $\sim 100 - \sim 10$ | Mesons annihilate converting energy into photons, electrons, and neutrinos. | |
| ~ 10 | Neutrinos are freezing-in during this period. $\rho_{\gamma} \cong 1.2 \times 10^9 \text{ g/cm}^3$ Same as for $\nu = \bar{\nu}^*$ except $\rho_{\mu} \sim 10^{-6}\rho_{\gamma}, \rho_{\pi} \sim 10^{-6}\rho_{\gamma}$ $\rho_{\nu} = (7/4)\rho_{\gamma}$ $\rho_{\nu} = (7/8)\rho_{\gamma}, \rho_{\pi} = (7/4)\rho_{\gamma}$ $t \cong 7.8 \times 10^{-3} \text{ sec}$ $t \cong 8.7 \times 10^{-3} \text{ sec}$ | |
| $\sim 10 - \sim 2$ | Continued adiabatic expansion of universe with $T_{\nu} \cong T$ despite negligible interaction of neutrinos with medium. | |
| ~ 2 | Start of electron-positron annihilation. $\rho_{\gamma} \cong 1.9 \times 10^8 \text{ g/cm}^3$ Same as $\nu = \bar{\nu}^*$ except $\rho_{\mu} = \rho_{\pi} \sim 0$ $\rho_{\nu} \cong (7/4)\rho_{\gamma}$ $\rho_{\nu} \cong (7/8)\rho_{\gamma}, \rho_{\pi} = (7/4)\rho_{\gamma}$ $t \cong 0.20 \text{ sec}$ $t \cong 0.22 \text{ sec}$ | |
| $\sim 2 - \sim 0.05$ | Electron-positron annihilation, converting energy into photons. Neutrinos cool adiabatically relative to remaining particles, the latter maintaining thermodynamic equilibrium. [See Tables I and II for more details during this epoch.] The neutron-proton abundance ratio reaches the free decay value, 4.5:1-6.0:1, at $T \sim 0.2$ Mev. Nucleogenesis begins at $T \sim 0.2$ Mev. | |
| ~ 0.05 | Nucleogenesis is well under way. $\rho_{\gamma} \cong 0.72 \text{ g/cm}^3$ $\rho_{\nu} \cong 0.72 \text{ g/cm}^3$ $\rho_{\mu} \cong 0.24\rho_{\gamma}, \rho_{\pi} \sim 0$ $\rho_{\nu} \cong 0.47\rho_{\gamma}, \rho_{\pi} \sim 0$ $t \cong 600 \text{ sec}$ $t \cong 550 \text{ sec}$ | |
| ~ 0.03 | Nucleogenesis essentially complete except for charge adjustment by β decay. $t \sim 30 \text{ min}$ | |
| $\sim 0.03 \text{ Mev}$ $\sim 1 \text{ kev}$ | Thermonuclear reactions among some of the light elements, viz., Li, Be, B, D with H, continue during this period. | |
| $\sim 0.015 \text{ ev}$ | At $t \sim 10^8 \text{ yr}, T \sim 170^{\circ}\text{K}$ and $\rho \sim 10^{-26} \text{ g/cm}^3$, galaxies probably form. | |

Timetable of events in the universal expansion (from the original paper by Alpher, James W. Follin and Herman²⁵).

continue to watch with considerable interest developments in a number of pertinent areas: the struggle to understand the formation of galaxies (see the article by Joseph Silk in *PHYSICS TODAY*, April 1987, page 28) in light of the high degree of isotropy of the background radiation; the search for short-wavelength deviations from the blackbody spectrum (see the news story on page 17), which may reveal details of processes at high redshifts; the use of the radiation background as an "absolute" frame of reference for the study of gross motions and preferred directions in this corner of the cosmos; and finally, the emergence of a remarkably precise value for the background temperature, making it possibly the best known of cosmological parameters. We look forward to the cosmological insights to be revealed by theoretical studies, by the increasing number of observational studies of the background radiation, by the Hubble Space Telescope and by the Cosmic Background Explorer satellite.

It has been exciting to have been involved in the early

development of the Big Bang model, to have witnessed the explosive development of work in this area, addressing as it does the fundamental concern for understanding the mystery of existence, and to have seen cosmology evolve from a skeptically regarded discipline not worked in by "sensible" scientists into one of the most popular and profound subjects in contemporary physics and astrophysics. The Big Bang model has survived for almost two generations—a very short time on any cosmic scale. What marvels of human imagination and understanding does the future hold?

Proper scientific credit does matter

By early 1967 Gamow and we had become very perturbed by how our early work continued to be ignored. Gamow took the initiative of urging a joint publication of a historical nature to attempt to set the record straight. The paper was published in the same year in the *Proceedings of the National Academy of Sciences*,² in the interests of speed. The main emphasis of the paper was documenting once more our work on the Big Bang model, especially our prediction of the cosmic background radiation, and our joint work on galaxy formation. More recent publications by us and by others have given accounts of that early work, and we have received a number of awards in its recognition. It is probably true that the publication in 1977 of Weinberg's *The First Three Minutes*³ had a major influence on the acceptance of contemporary cosmological ideas by the scientific community. Obviously Weinberg consulted original source material in preparing his book; unfortunately other authors have not.

Accounts continue to appear in the scientific literature and in popularizations that deal incorrectly with the early work by us and by Gamow, particularly on the question of the cosmic background radiation. Too many authors evidently rely on nearly contemporary publications, which incorporate previous errors, rather than consulting original source material. One wonders about the forces that shape the activities of some scientific authors.

These questions need to be looked at with proper objectivity by historians and sociologists of science, particularly in terms of what such events say about scholarship and integrity in science, which is one of the most important of human endeavors. We take exception to statements by some that correct attribution does not matter, that only the furtherance of science matters. This view does not reflect the ideals and realities of the scientific enterprise. The correctness of the history of science does matter, both for the present and for the future.

We, the authors of this article, are now in a position to have contemplated some of the advantages and disadvantages of living for a relatively long time. It has been amusing to note that there are occasions when colleagues discuss this subject as though we are no longer either living or scientifically productive. But we have derived enormous pleasure from the creative process, considerable pain from lack of appreciation of our work, and some measure of satisfaction and pleasure from realizing that at long last some scientific colleagues view our early contributions as meritorious. It was very pleasant to have a distinguished cosmologist remark to Alpher during one of the early Texas Symposia on Relativistic Astrophysics, "You guys did it all."

* * *

This historical exposition on the physics of the Big Bang cosmological model is a synthesis of separate but coauthored invited presentations at a symposium of the divisions of astrophysics and history of physics held during the Washington meeting of

The American Physical Society in April 1987, and is part of the basis of a book in preparation. Much of the technical material was presented earlier, at the April 1951 Washington meeting of the APS, as a joint invited paper.

References

1. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle, *Rev. Mod. Phys.* **29**, 547 (1957). R. V. Wagoner, W. A. Fowler, F. Hoyle, *Astrophys. J.* **148**, 3 (1967).
2. R. Alpher, G. Gamow, R. Herman, *Proc. Natl. Acad. Sci. USA* **58**, 2179 (1967).
3. G. Gamow, *Creation of the Universe*, Viking, New York (1952). P. J. E. Peebles, *Physical Cosmology*, Princeton U. P., Princeton, N. J. (1971). F. Reines, ed., *Cosmology, Fusion and Other Matters: George Gamow Memorial Volume*, Colorado Assoc. U. P., Boulder (1972). S. Weinberg, *Gravitation and Cosmology*, Wiley, New York (1972). S. Weinberg, *The First Three Minutes*, Basic Books, New York (1977; second edition, 1988). E. R. Harrison, *Cosmology*, Cambridge U. P., New York (1981). J. Bernstein, G. Feinberg, eds., *Cosmological Constants: Papers in Modern Cosmology*, Columbia U. P., New York (1986).
4. A. A. Penzias, R. W. Wilson, *Astrophys. J.* **142**, 419 (1965). R. H. Dicke, P. J. E. Peebles, P. G. Roll, D. T. Wilkinson, *Astrophys. J.* **142**, 414 (1965).
5. R. Alpher, *Phys. Rev.* **74**, 1577 (1948).
6. F. Hoyle, *The Nature of the Universe*, Harper, New York (1950).
7. R. Alpher, R. Herman, *Nature* **162**, 774 (1948).
8. R. Alpher, R. Herman, G. Gamow, *Phys. Rev.* **74**, 1198 (1948).
9. R. Alpher, R. Herman, *Phys. Rev.* **74**, 1737 (1948).
10. R. Alpher, R. Herman, *Rev. Mod. Phys.* **22**, 153 (1950).
11. G. Gamow, *Ohio J. Sci.* **35**, 406 (1935).
12. G. Gamow, *J. Wash. Acad. Sci.* **32**, 353 (1942).
13. G. Gamow, *Phys. Rev.* **70**, 572 (1946).
14. R. Alpher, H. A. Bethe, G. Gamow, *Phys. Rev.* **73**, 803 (1948).
15. G. Gamow, *Phys. Rev.* **74**, 505 (1948).
16. G. Gamow, *Nature* **162**, 680 (1948).
17. D. T. Wilkinson, P. J. E. Peebles, in *Serendipitous Discoveries in Radio Astronomy*, K. Kellermann, B. Sheets, eds., Natl. Radio Astronomy Observatory, Green Bank, W. Va. (1983).
18. H. A. Bethe, *Elementary Nuclear Theory*, Wiley, New York (1947).
19. R. Alpher, R. Herman, *Phys. Rev.* **75**, 1089 (1949); **84**, 60 (1951).
20. R. Alpher, R. Herman, *Proc. Am. Philos. Soc.* **119**, 325 (1975).
21. F. Hoyle, R. J. Tayler, *Nature* **203**, 1108 (1964).
22. J. S. Smart, *Phys. Rev.* **74**, 1882 (1948); **75**, 1379 (1949).
23. J. H. Applegate, C. J. Hogan, R. J. Scherrer, *Phys. Rev. D* **35**, 1151 (1987).
24. C. Hayashi, *Prog. Theor. Phys. (Japan)* **5**, 224 (1950).
25. R. Alpher, J. W. Follin, R. Herman, *Phys. Rev.* **92**, 1347 (1953).
26. R. Alpher, J. W. Follin, R. Herman, *Phys. Rev. A* **91**, 479 (1953). J. W. Follin, R. Alpher, R. Herman, *Bull. Am. Phys. Soc. Ser. II* **4**, 476 (1959); **5**, 287 (1960).
27. R. Alpher, R. Herman, *Science* **128**, 904 (1958).
28. R. A. Matzner, *Astrophys. J.* **154**, 1123 (1968).
29. L. A. Rawley, J. H. Taylor, M. M. Davis, D. W. Allan, *Science* **238**, 761 (1987).
30. J. R. Gott, J. E. Gunn, D. N. Schramm, B. M. Tinsley, *Astrophys. J.* **194**, 543 (1974).
31. R. V. Wagoner, *Astrophys. J.* **179**, 343 (1973).
32. G. Gamow, *Mat.-Fys. Medd.* **27**(10), 1 (1953); *Vistas Astron.* **2**, 1726 (1956).
33. A. G. Doroshkevich, I. D. Novikov, *Sov. Phys. Dokl.* **9**, 111 (1964).
34. G. Gamow, *Rev. Mod. Phys.* **21**, 367 (1949).
35. W. S. Adams, *Astrophys. J.* **93**, 11 (1941). A. McKellar, *Pub. Dom. Astrophys. Obs. Victoria B. C. Can.* **7**, 251 (1941). ■

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