THE BIG BANG MODEL: ITS ORIGIN AND DEVELOPMENT

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ABSTRACT. The current Big Bang Model had its origin in Einstein's attempt to model a static cosmos, based on his general theory of relativity. Friedmann and Lemaître, as well as de Sitter, further developed the model to cover other options, including nonstatic behavior. Lemaître in the 1930s and, particularly, Gamow in 1946 first put physics into the nonstatic model. By 1946 there had been significant developments in the mathematics of the model due to Robertson, Walker, Tolman and many others. The Hubble law had given an essential observational basis for the Big Bang, as did the attribution of cosmic significance to element abundances by Goldschmidt. Following early suggestions by George Gamow, the first attempt to explain nucleosynthesis in a hot, dense, early universe was done by Alpher, Bethe and Gamow in 1948, a paper whose principal importance was that it suggested that the early universe was in fact hot and dense, and that hydrogen and helium and perhaps other light elements were primeval. In that same year Alpher and Herman first predicted a cosmic background radiation at 5 kelvin as an essential feature of the model. The Hubble expansion rate, the primordial and stellar abundances of the elements, and the cosmic microwave background are major pillars today for the Big Bang model.

Key words: History of Astronomy: general relativity: Big Bang.

I am pleased to have been invited to this special George Gamow memorial session. Its been a long time association for me. I first met Gamow in early 1942, 57 years ago.

I wish I could have been here, but I am sure Prof. Chernin will do an admirable job at reading my communication. It has been more than 50 years since the alpha-beta-gamma (Alpher, Bethe and Gamow) paper on prestellar nonequilibrium nucleosynthesis was published, and since the late Robert Herman and I predicted a consequent present cosmic background radiation at about 50°K. Herman and I worked closely with Gamow from the late 1940s until his death, and we much say that he was at least a spiritual guide even in the research in which he did not participate. A day does not go by without my remembering Gamow, and his love for physics and cosmology.

Introduction of physics into cosmological modeling.

Modern mathematical modeling of the universe began with Einstein. In 1917 he developed the first general relativistic model of the cosmos with assumptions that the universe was homogeneous and isotropic, and that the smearing out of all structure, averaged over the universe, led to a single cosmic density of matter. This material was taken to be a dilute ideal gas with an appropriate equation of state. This, together with an equation for the conservation of energy in a comoving volume, as well as Einstein's basic field equations which relate the curvature of space-time to the cosmic content of energy and momentum, provided the description of the model.

The then-current wisdom was that the universe was static, and that the peculiar velocities of objects in the heavens were certainly nonrelativistic. The model was inherently unstable, which led Einstein to add a term containing a "cosmological constant" to force stability. Covariance was preserved. Einstein's concluding statement in his paper was "That term is necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars".

While this added feature did not damage the mathematics particularly, Einstein apparently felt somewhat embarrassed later when the Hubble law, which synthesized observational evidence for a general cosmic expansion, was published in the late 1920s. He is widely quoted as having said that the introduction of this constant, Λ, was his "greatest blunder". Einstein may have sold himself short. A nonzero Λ has been used from time to time to reconcile the age of the universe with the age of contained structures. Gamow, Herman and I did this when the Big Bang was under attack for giving too short an age. Alternatively, some cosmologists studying the possibility of inflation in the early universe introduce Λ. There is recent evidence based on Type 1a supernovae that the universe is open, i.e., that the mean density of matter and radiation is significantly less than a critical density and that the expansion shows acceleration at large distances. The origin of this acceleration may be Λ acting as

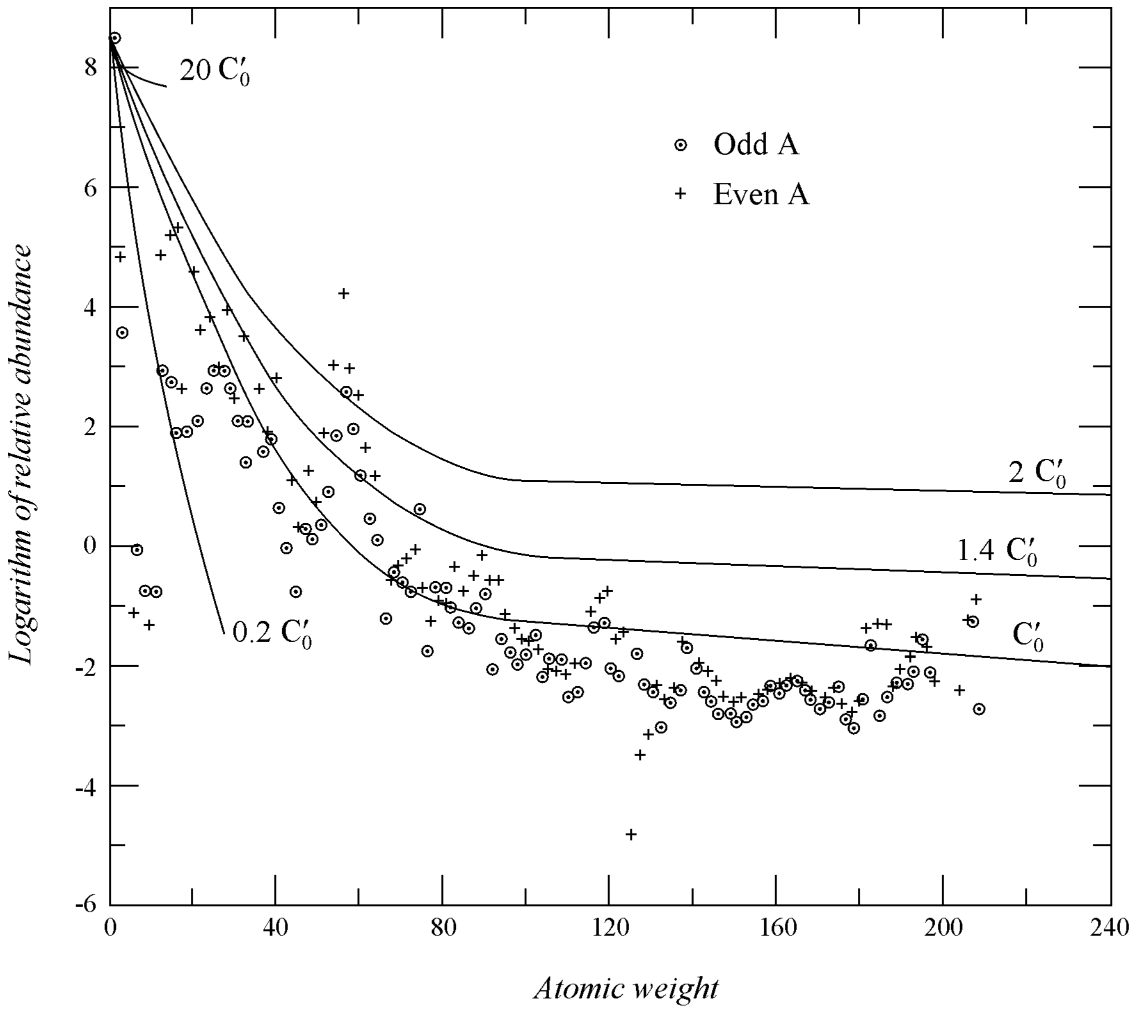

Figure 1: Comparison of observed relaive abundances with results of simple prestellar neutron-capture sequence calculation. Starting conditions are $T = 0.11$ MeV and time=140 seconds (published in 1950), with $C_0^{'}$ being the starting baryon concentration (about $10^{17} cm^{-3}$).

a repulsive driving force, or, as has been suggested recently, in a phenomenon called "quintessence", which is a fluctuating dynamic driving force.

Relative Abundance of the Elements.

In the early years of this century physical chemists, working with limited knowledge of the relative abundance of the chemical elements, concluded that these abundances must reflect nuclear rather than chemical properties. Over the next several decades determinations of the relative abundances in various cosmic locales improved, culminating in the late 1930s with the work of a geochemist, V.M. Goldschmidt, who constructed a relative abundance table which became accepted as being cosmic. This was a profound step forward, in the sense that the elements must have been formed in locales of rather extreme physical conditions, such as the interior of stars, or, as first suggested by Gamow, in some early configuration of the universe, a locale suitable for thermonuclear reactions.

Study of the composition of the universe is much more than a cottage industry among astronomers and geochemists, since improvements in the data give further clues both to phenomenology in the early universe, and in interstellar space, as well as to the formation and evolution of stars. In particular increasing attention is being paid to the abundances of the lightest elements, since it is now almost certain that these elements were formed by thermonuclear processes in the early stages of a hot, dense expanding universe which has evolved into what we see now, while all the other elements in the periodic table are formed later primarily in stellar interiors. They are then released either in the violent outburst accompanying the death of stars as stars exhaust their source of fusion energy, or from thermonuclear explosions in the atmospheres of white dwarfs as they accumulate critical masses of material from a neighboring star in binary systems.

A graph exhibiting cosmic relative abundances according to data in the 1950s is given in Figure 1, which shows also the best fit Herman and I could obtain with neutron-capture reaction sequences. The free parameter is related to the density of matter at the onset of nucleosynthesis.

Expansion of the Universe

Studies of the rate of expansion of the universe as well as the mean density of matter, particularly as these relate to the reality of measurements of acceleration at large redshifts, is an active area of cosmological research.

In the early days of our work on the standard Big Bang model, the calculated age of the Big Bang was less than the much-better-known age of the Earth. This was a major deterrent to any wide-spread acceptance of the Big Bang model at the time, and led to a period in which the steady state model was ascendant. It was possible to resolve the age discrepancy by invoking a nonzero value of Λ, but that was generally thought not to be appropriate at the time. Criticism of the Big Bang model by the steady state school was in our view unduly harsh, given the inherent difficulties in determining the requisite parameters. Moreover we felt that the steady state model had more deficiencies than the Big Bang. Refinement of values of the Hubble parameter and the mean density, as well as improved ages for galactic clusters, are leading to acceptable ages for the universe and its contents.

Development of mathematical nonstatic models

Some years after the Einstein model was described, Alexander Friedmann, in the Soviet Union, with whom Gamow studied relativity theory, studied nonstatic models with an arbitrary cosmological constant (1922 and 1924). Such nonstatic solutions were explored, apparently independently, by Georges Lemaître, a Belgian cleric, in 1929-1930.

Some of us now to refer to the Friedmann-Lemaître-Robertson-Walker equation as the basic equation of the Big Bang, giving the latter two men recognition for the explication of a line element for the model.

By 1929 cosmic expansion had come to be widely accepted, and Lemaître became the first to discuss some physics involved in a nonstatic model. He tried to reconcile the model with Hubble's observed expansion rate and mean density of matter in the universe. The bottom line in Lemaître's work at the time was his particular interest in explaining the origin of cosmic rays. His idea was that the cosmos began as a all-encompassing gigantic nucleus which broke up into nuclear-sized pieces. Some of these nuclear pieces came away from the breakup with very high energy, he suggested, and might have survived to be identifiable as cosmic rays. Current views are that cosmic rays originate in supernova explosions as well as from the conversion of photons from gamma-ray bursters. Many years later (1948) Maria Göppert-Mayer and Edward Teller again proposed a single cosmic nucleus whose breakup served as the origin of all matter and energy in the universe. It appears that Lemaître should be c redited as being the first to try to introduce some physics into modeling. It also appears that the next scientist to try to do this was George Gamow.

George Gamow's Early Foray into Cosmology

In 1935, Gamow noted the discovery of the neutron and the consequent study of neutron-capture reactions by Enrico Fermi in Italy. This led him to suggest that such reactions established the abundance distribution of nuclear species, and that neutrons undoubtedly played a role in reactions producing energy in stars (a precursor of the s-process in stellar nucleosynthesis). In 1942 he again suggested that the elements were formed somehow by nuclear reactions in a system not in thermodynamic equilibrium. In 1946 he published a more specific set of ideas on nuclei being formed in the early universe. He was motivated toward this end by the failure of global equilibrium theories of element synthesis.

In 1946 it was still Gamow's hope to find a single locale for explaining the entire abundance distribution. Given the difficulties with single locale equilibrium theories he posited that the early expanding universe would have physical conditions suitable for nuclear reactions to occur in a nonequilibrium manner over a short period of time and then be quenched by dilution in the expansion and by the exhaustion of starting material. He went on to propose that nuclei could be built up from an initial neutron gas by some means of agglomeration, with the final states being arrived at by intervening beta decay of neutron-rich fragments into more stable nuclei. In 1945 I had completed a master's dissertation on sources of energy in stars and was accepted by Gamow to work on a Ph.D. dissertation. After I was scooped by E. Lifshitz in the Soviet Union on my first dissertation topic on the growth of instabilities in a relativistic expanding medium, we picked a second dissertation topic, namely, developing the rather primitive 1946 ideas of Gamow on element building.

I arrived at The Applied Physics Laboratory of the Johns Hopkins University (APL/JHU) in 1944, and shortly thereafter met Herman who had been there for

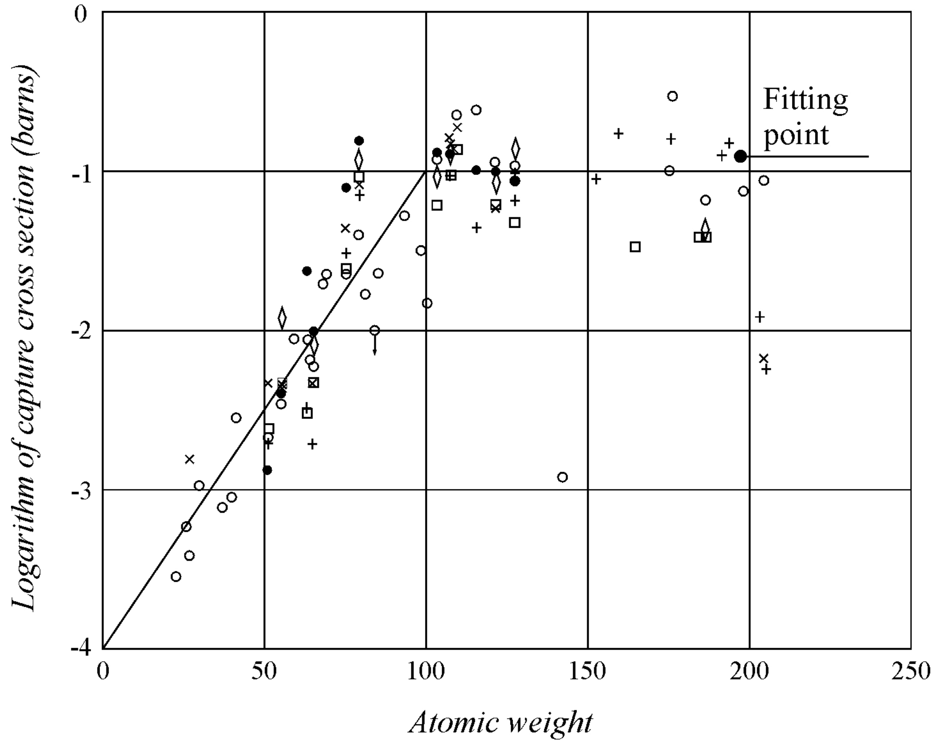

Figure 2: Probability of (n,γ) reactions as published by Donald Hughes (Argonne), measured with 1 MeV neutrons. Other avaliable data are also shown (1950 plot).

several years. When the war ended, we both joined a newly formed Research Center, We had a commonality of interest in astrophysics and cosmology, and almost daily discussions ensued with Herman, and of course with Gamow, who became an APL/JHU consultant after the war. Our official tasks at APL/JHU were on very different matters.

The Alpher-Bethe-Gamow Paper

The alpha-beta-gamma theory was the result of my second foray into cosmology. We proposed to see if we might understand the synthesis of the chemical elements in a hot, dense early phase of the expanding universe. The success of such a program would be judged by how well the calculations matched the presently observed cosmic abundances of the elements. We hoped that one theory would explain it all.

The mathematical model for consideration of the early universe was based on the Friedmann-Lemaître-Robertson-Walker line element. Given the anticipated high ambient temperatures, it was expected that the total density and the consequent dynamics of the universe was dominated by radiation (R.C. Tolman in 1934 discussed a model consisting of blackbody radiation). It was not clear how much of the total density at early times to ascribe to the matter then present, except we expected it would make a very small contribution, and its numerical value would be determined by the conditions for synthesizing the elements. The main stumbling-block initially was our lack of detailed knowledge of the cross sections for the various kinds of nuclear reactions among the species likely to be present.

We had just emerged from World War II, and data for such reactions, under conditions of high temperature and density, were still classified or were just beginning to be declassified. As luck would have it, we got a boost from the work of Donald J. Hughes, then at Argonne, and later at Brookhaven. Hughes surveyed any and all materials which might be of interest in reactor construction using neutrons at energies of about 1 MeV (about 10^{10} °K, which, incidentally, would have been the cosmic temperature at about a second into the expansion), and measured the cross sections for (n,g) reactions. The exciting result of his work is shown in Figures 2, 3. The top diagram shows the variation with atomic weight of the neutron-capture cross-sections, where one should note the exponential rise of the probability to an atomic weight of about one hundred, and essential constancy for heavier nuclei, a mirror image of the run of abundance data. The second diagram is a correlation of the probability of neutron-capture reactions with abundances. This was all quite suggestive.

On this basis we undertook to calculate in a very approximate way the growth of abundances by neutron-capture reactions. We assumed that the initial material

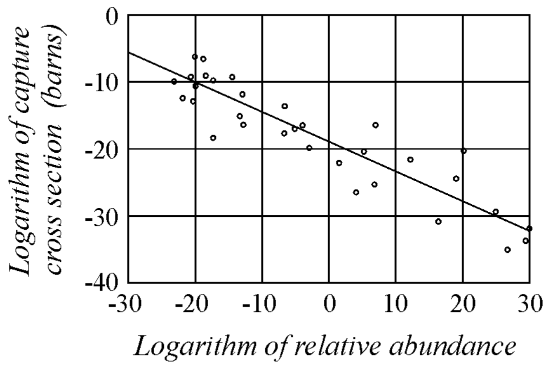

Figure 3: Correlation of reaction cross sections with observed relative abundances.

was a neutron gas, with a density being chosen to give the best subsequent representation of observed abundances. Hughes' neutron-capture reaction cross sections were corrected to 0.1 Mev by 1/E (to be well below photodissociation energies), and followed the general run of the probabilities shown in Figures 2 and 3, with the successive reactions beginning with the capture of a primordial neutron by a newly formed proton resulting from neutron beta-decay (half-life of about 800 seconds). The nucleus thus formed would have been a deuteron; next the deuteron would have absorbed a neutron to form a triton, the nucleus of tritium, the heaviest isotope of hydrogen. And so on. Clearly at this point we had to gloss over any details in cross sections. When nuclei so formed had an overabundance of neutrons and were therefor unstable, be ta-decay would have adjusted the relative number of neutrons and protons toward the valley of stability. Then successively heavier nuclei which formed would in turn adjust by beta-decay so as not to be overly neutron-rich and would then be stable on a time scale of the order of the duration of the period of formation of nuclei. For purposes of a calculation one could carry out at a time when digital computers were scarce, it was assumed that the reaction rates would be fast compared to the rate of expansion of the universe, and therefore the calculations dealt basically with a static model.

This very simplified calculation led to what then seemed a very exciting representation of the overall cosmic abundances of nuclei, as illustrated in Figure 1. Moreover the calculation rationalized the high relative abundance of helium (an aspect of relative abundance data which had long been puzzling). I should mention that Bethe was not associated with the alpha-beta-gamma paper, but did not object to his name being added on the grounds that the result might even be right.

Standard Big Bang Models studied by Alpher and Herman

After the alpha-beta-gamma manuscript had been sent in, Herman and I proceeded immediately to reconsider the entire calculation in a series of papers, with the intent of removing some of the assumptions which had been made. There was one particular problem, recognized early on, that nature had not provided us with sufficiently stable nuclei at atomic weights 5 and 8, so that the notion of a sequential build-up of nuclei by neutron capture could not be correct in detail for the light elements.

The one free parameter whose value we chose in model calculations was the density of matter at a particular epoch in the expansion, and it was satisfying that the value we found later with improved calculations was close to that chosen in the alpha-beta-gamma paper.

In late 1949 I gave a colloquium with Enrico Fermi in the audience. Fermi was intrigued with our lack of nuclear reaction data for the light elements; when he returned to Chicago he enlisted his colleague, Anthony Turkevich, a nuclear chemist, and between them they developed a list of some 28 reactions among the light elements, using observations of reaction rates where they were available, and using nuclear theory, as well as educated intuition, to estimate other rates. Their results were most interesting, and we show them in Figure 4. For brevity I have chosen not to show some of the intermediate solutions Herman and I produced. Fermi and Turkevich used ambient conditions similar to those in the alpha-beta-gamma paper and sent their results to us to be included in an extensive review paper Herman and I wrote in 1950 on the general problem of the origin of the elements. They too were stymied by the gap due to the lack of nuclei at atomic weights 5 and 8, as was Eugene Wigner in a separate encounter.

Starting Conditions for Nucleosynthesis.

Our starting conditions for primordial nucleosynthesis had been primitive. A major improvement was due to Chushiro Hayashi of Japan in 1950. The universe was surely hotter and denser before nucleosynthesis began; in all of our earlier calculations, including those of Fermi and Turkevich, the ratio of neutrons to protons at the start of element-building was taken to be what resulted from the free decay of primordial neutrons prior to a specific starting time at about 0.1 Mev. (See Figure 5 for a listing of relationships inherent in the Big Bang model. In particular, note the power law relation involving the densities of matter and radiation). Hayashi proposed that the ratio of neutrons and protons be whatever resulted from spontaneous and induced beta-decay processes in the early stages of the expansion, in the presence of electrons, positrons, neutrinos and antineutrinos. Element building would then proceed with the consequent neutrons

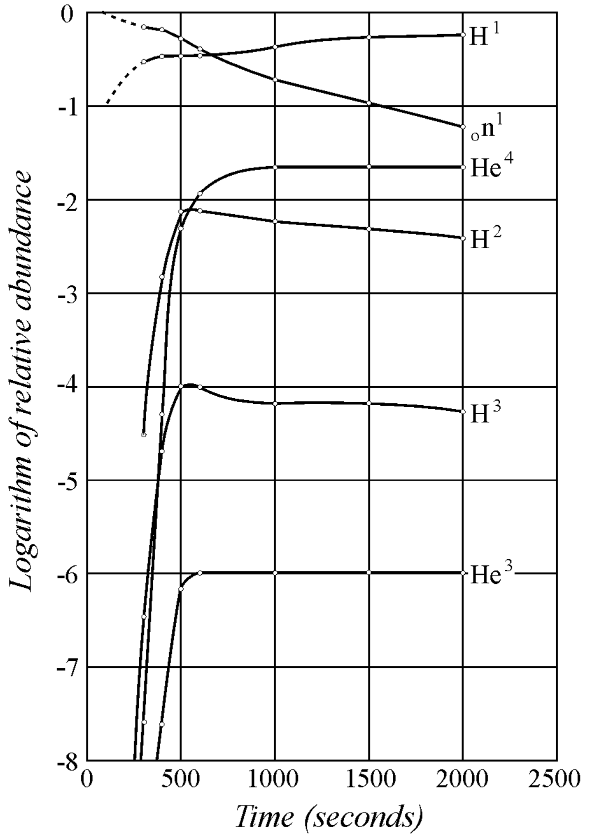

Figure 4: Calculation of light element relative abundances by Enrico Fermi and Anthony Turkevich, using ambient conditions as described in the Alpher-Bethe-Gamow paper in 1948. Fermi and Turkevich asked that their work be published in a 1950 review of the origin of the elements by Alpher and Herman. They surveyed 28 nuclear reactions with reaction probabilities either as measured or as they estimated them to be. They also were unable to bridge the gap at atomic weights 5 and 8, but confirmed the high abundance of helium, as had our earlier work.

and protons present as the temperature dropped low enough to rule out any photodissociation reactions.

Hayashi's calculation gave values of the neutron-proton ratio which precluded a successful generation of the relative abundance distribution by our simple neutron-capture picture. There were some difficulties with his calculation, and Herman and I were joined by James W. Follin, Jr., in 1953 in an improved approach, which has become a more-or-less standard starting point for modern nucleosynthesis calculations.

In our 1953 paper we did not go so far as predicting the resulting relative abundance distribution of the elements. We did such calculations later but they were given only in some short presentations at meetings of the American Physical Society prior to 1965. Herman and Gamow and I went on to other positions in 1965, while Follin stayed at Johns Hopkins, a situation which made it difficult to put together a detailed paper (no electronic mail then). Others did such calculations later, using detailed reaction probabilities which were becoming available. We did determine that improved initial conditions still did not obviate the difficulties with the atomic weight gaps at 5 and 8. It was also clear that the initial conditions, and subsequent nucleosynthesis, would depend significantly on the neutrino types introduced into the calculation. One interesting consequence of these calculations was the realization that prior to the onset of nucleosynthesis all of the reactions between neutrons, protons, radiation, and the other elementary particles present went on so rapidly compared to the rate of universal expansion that the mixture was basically in thermodynamic equilibrium. If one accepts the premises of thermodynamics, then it must be so that the equilibrium state conceals any prior history of the system, which has give us pause from time to time about inflationary models.

Nevertheless, it seems sensible to consider some phenomena associated with the earliest times in the expansion which survived the equilibrium period, such as the present nonexistence of magnetic monopoles, the present preponderance of matter over antimatter, the existence of very small fluctuations which somehow survived to become the anisotropies observed in the cosmic microwave background radiation by the COBE satellite and in other recent observations, and the question of how the early universe came to be at such a uniform temperature.

There are other interesting consequences of the detailed examination of the state of the universe just prior to nucleosynthesis. When, in the expansion, temperatures were greater than the rest mass energy of baryons these would be created and destroyed freely. When the temperature dropped below this value, the then extant abundances of neutrons and protons would be frozen in, until reactions ensued, except for radioactive decay of the neutron. Later, when the temperature had dropped to a value of less than the rest mass of a pair of leptons, the abundance of electrons and positrons relative to one another would have frozen in. In a similar vein, one can show that neutrinos and their antiparticles would have frozen in, at a temperature whose precise value depends on whether the neutrinos oscillate, have a nonzero mass, and on the number of colors. Because the interaction of neutrinos with other matter and radiation is extremely small, the neutrinos should then have participated in the expansion and cooling of the universe as though they were a radiative component, and there should now be a background of neutrinos which has cooled down to a temperature of the order of 2 kelvin. Their number density should be comparable to the number density of 2.8 kelvin photons, but there seems to be no observational procedure waiting in the wings for detecting these low energy background neutrinos.

I would make two further comments about our early

$R(t)$ = expansion scale factor.
Redshift $z = \frac{\Delta\lambda}{\lambda}$.
Consrevation of baryoms throughout expansion
$\rho_m R^3 = constant$ or $\rho_m = \rho_{m,0}(1+z)^3$.
Adiabatic expansion of radiation throughout expansion
$\rho_r R^4 = constant$ or $\rho_r = \rho_{r,0}(1+z)^4 = \frac{\alpha T^4}{c^2}$.
Hence $\rho_r \rho_m^{-4/3} = constant$ throughout expansion and Temperature $T = T_0(1+z)$.
At early times $T = \frac{1.52 \cdot 10^{10}\ ^\circ K}{\sqrt{t}} = \frac{1.31 MeV/k}{\sqrt{t}}$,
where t is in seconds. (Numerator=universal constants).
At early times, $\rho_m << \rho_r$ and $\rho_m \propto t^{-3/2}$

Figure 5: Basic relationships in the Big Bang

work on nucleosynthesis. The very simplified model we used predicted abundances of lithium, beryllium and boron which were high compared to observation. In 1948, Gamow, Herman, and I reported a calculation wherein we showed that once the neutron-capture sequence was essentially done, the temperature was still high enough so that the remaining nuclei could interact with the abundant protons present, which would reduce the abundances of these light elements by appropriate amounts. Recent work on primordial deuterium abundance seems to contradict this. A second comment has to do why one does not observe equal numbers of nucleons and antinucleons in the universe. In our work Herman and I showed that the present asymmetry could not be the result of a statistical fluctuation in the early universe. At the time of our study we argued that the abundance of antinucleons relative to nucleons must be less than one part in 10^7, since anything greater than this would be able to account for all the energy generation in our galaxy or in the cosmos as a whole. Much more recent work on this question suggests that there was a basic symmetry-breaking in reactions at high temperatures in which nucleons go into antinucleons, and vice versa, with a consequent favoring of a final abundance ratio of far less than a part in 10^7.

Further Development of Nucleosynthesis Calculations

In 1957 a seminal paper was published by Burbidge, Burbidge, Fowler and Hoyle, who did a fine job of explaining the relative abundances of most of the heavier elements as having been generated in stellar interiors, with modification and distribution in space of the synthesized elements when the stars ran out of nuclear fuel and went into a collapse and explosion mode.

The synthesis of light elements was still problematical in the scheme of things among steady state theorists until Hoyle and Tayler, in 1964, used the Alpher-Follin-Herman methodology to conclude that helium must have been generated by light element reactions in the early universe. This was a major step forward (or backward, depending on your predilections for cosmological models) for these authors, since they were strong advocates of a steady-state model of the universe, with no hot dense early universe to make light elements. They also noted that the calculations were somewhat sensitive to the assumed types of neutrinos for the pre-nucleosynthesis era, as we had found in 1953. A light element calculation using our methodology was done by Peebles in 1966, with useful results for the abundances. The first full-scale light element calculations were carried out in 1967 by Robert Wagoner, Willie Fowler and Fred Hoyle, in the context of the standard Big Bang model as well as in massive stars, ca. 10^8 solar masses, then thought to be possible alternative sites. The latter long since vanished as a viable option.

In 1973 Wagoner carried out an improved calculation of light element abundances, and the computer code he developed, with modern updates, is still in use by those examining such abundances. As we have mentioned several times earlier, the one free parameter in Big Bang nucleosynthesis calculations is the extant density of matter when such reactions became important. Wagoner's work strongly indicated that if observed deuterium abundances were primordial, then the required matter density was well below what would be needed in present observations to close the universe. This seems still to be the case. Its value is the subject of much of observational cosmology. Recent observations appear to favor a value of the ratio of total density of baryons to the density for closure, $\Omega < l$,. It now seems clear that the value of Ω may in fact be more than can be inferred from the requirements of nucleosynthesis, so that there may still be a need for dark matter. But W may not be as large as 1 , as researchers on the inflationary model of the universe would insist it has to be, although the deficiency may actually reflect a vacuum energy density causing acceleration of the universe.

Since the Wagoner paper of 1973, there has been a considerable effort in improving the abundance calculation for light elements. We have reproduced in Figure 6 a state-of-the-art calculation of light element abundances compared with observation in the standard Big Bang model, from a paper by Schramm and Turner in 1998. The use of the present matter density as a variable follows from the simple power law already mentioned, namely, $\rho_r \rho_m^{-4/3} = constant$ throughout the expansion.

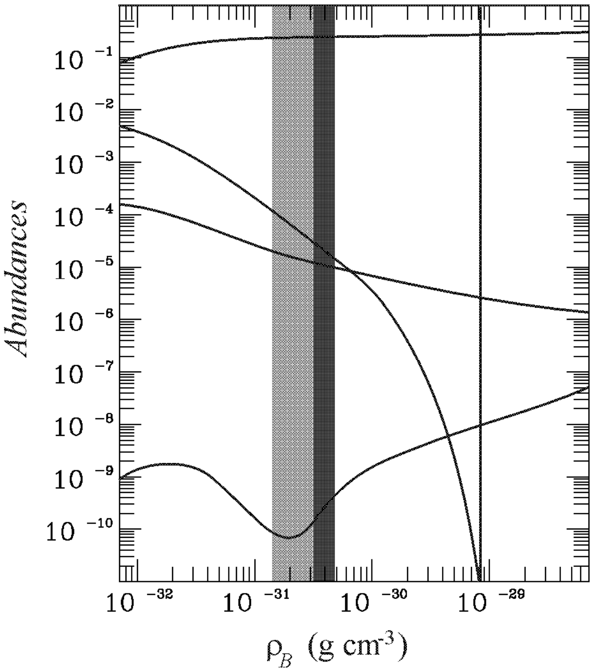

Figure 6: The most recent publishrd calculations of prestellar rewlative abundances, as published by Schramm and Turner in Reviews of Modern Physics, 1998.

Neutrinos in the Early Universe

We have characterized the simple Big Bang picture of nucleosynthesis as depending on one free parameter, namely, the density of matter during nucleosynthesis. However, as was found in the Alpher-Follin-Herman study, and in subsequent developments of nucleosynthesis calculations, the initial conditions for this period involve the choice of the number of neutrino families. This choice affects the density history prior to and during nucleosynthesis; most modern calculations indicate that the best choice is three families of neutrinos and their antiparticles. Some researchers conclude that the calculations suggest an upper limit of four families, so the matter may not be completely settled. Nevertheless, it appears currently that three is a good number, and subsequent to the statements supporting this, it was shown by experiments at CERN that there were indeed three. With the prediction of the background radiation, and the prediction that there should be three families of neutrinos, we have two cases in which cosmological prediction really preceded terrestrial observations.

If neutrinos indeed have nonzero mass, they would contribute significantly to the mean density of matter in the universe, although calculations suggest that while they are numerous, with number densities like those of photons, they are probably not massive enough to influence the formation processes in stars and galaxies, and would not yield a high enough density of all matter to make the universe closed.

The Initial Singularity in the Big Bang

The basic equations describing the Big Bang model, show a "singularity" at zero time. To put it differently, without introducing some new physical ideas, we would conclude that regardless of where one is in the universe, one would find an infinite density and an infinite temperature at the origin of time $t = 0$. Is there a simple way of avoiding this dilemma? Perhaps not, for Steven Hawking and Roger Penrose some years ago showed that a singularity was an inevitable concomitant of relativistic models of the universe, and of black holes. There are several ways which may possibly get around this dilemma. One which we have already mentioned is to consider that early in the standard model, prior to nucleosynthesis, there was a state of equilibrium which effectively screens us from knowing what went before such a state. Some would say that this is statement is "technobabble", and is not different from ascribing "creation" to a "Prime Mover" or other extramundane entity. A second is to invoke an "inflationary model" of the early universe, in which just after $t = 0$ the universe underwent one or more of a variety of changes from an initial vacuum state, time, matter and radiation coming into being. Models involving "quantum gravity" and inflation are outside the scope of this paper.

The Formation of Structure in the Universe

There is virtually no end of problems one may list which remain for cosmological modeling. One which has seen much activity during our lifetimes is the origin of structure in the cosmos. It is worth a comment that for the period of time when the microwave background radiation was thought to be remarkably isotropic, cosmologists were concerned about the formation of structure in a medium with no "seeds" for nucleation present. The observation of the 10^{-5} level departures from isotropy after several years of COBE data taking removes this concern, even though the transition to observed structure is not yet understood.

A major problem in all these matters is the now agreed-upon fact that the luminous matter by which we study objects in the heavens may only be a fraction of the matter present in these objects. There is "missing mass", whose nature is still not known. It is almost surely not all baryonic, for baryons in the required densities would have participated in early nucleosynthesis in the expanding universe and would have destroyed any agreement between theory and current observa-

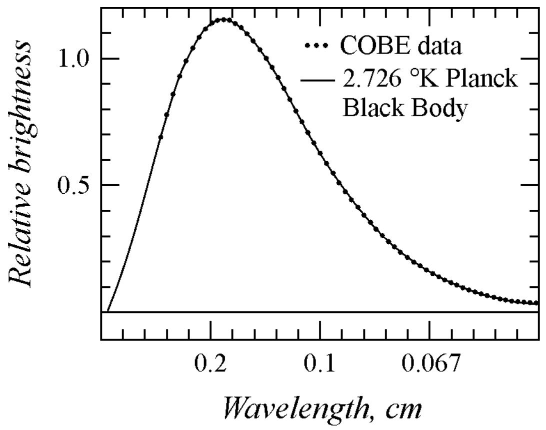

Figure 7: Measurement of the cosmic microwave background radiation carried out by the COBE satellite (John C. Mather, principal investigator at NASA-Goddard). The plot involves literally millions of data points, accumulated over four years, and is without doubt the most precise black body spectrum ever measured, with T = 2.726 kelvin as an extraordinarily accurate cosmological parameter. Error bars on the measurements lie within the width of the fitted line.

tion. The matter could not be very hot, because the chance of being captured by gravity in galaxies and clusters of galaxies would have been quite small. It might be some form of cold matter; or it might be condensations of matter into nonstellar objects. But again such objects would be baryonic, and the requirements of nucleosynthesis provide an upper limit on the number and mass of such objects. Nevertheless astronomers are seeking such objects, and new techniques are being employed, as for example, gravitational lensing or microlensing. The reality of such lensing, predicted by general relativity, has been amply demonstrated

The Cosmic Microwave Background (CMBR)

I have saved for last a discussion of the cosmic microwave background radiation (CMBR), work in which Herman and I have taken a lot of pride, but which also has caused us many problems. Let me return to the beginning of our CMBR foray. In the summer of 1948 Gamow was resident at Los Alamos, and sent us a draft of a short paper he was sending to *Nature*. There were some typically Gamowian problems with his paper, which dealt with a simplified view of light element nucleosynthesis, and consequences for galaxy formation, with essentially the same initial conditions which were developed in the alpha-beta-gamma paper. What these errors were is now of no interest, but suffice it to say that we pointed out the errors to him, and he encouraged us to submit a companion paper to *Nature*. I might mention that in his paper Gamow tried to calculate the size of a typical galaxy based on the conditions for primordial nucleosynthesis and using the Jeans criterion for condensations. In preparing our paper, Herman and I found that we could integrate the Friedmann-Lemaître-Robertson-Walker equations without approximation, and obtained a relationship connecting the densities of matter and radiation at any selected times in the cosmic expansion. (We quickly realized that it was far simpler to use the power law in Figure 5). In this 1948 note in *Nature* Herman and I said "... and the temperature in the universe at the present time is found to be about 5°K".

We published the procedure we used, as well as the results, in a number of papers in the next few years, and carried on a friendly argument with Gamow for several years on two major points. For one, he doubted that our calculation had any particular meaning, and for another, if there was a background radiation its observation in the vicinity of the earth would be confused with other radiation (Teller used the same argument), such as integrated starlight, providing comparable energy densities. We did point out the difference in the resulting spectrum. Gamow basically capitulated when in a 1950 paper he stated that the background temperature is 3°K, without any indication of where he got the number. It turns our that calculating the background radiation temperature in the Big Bang is absurdly simple. We noted that early in the expansion the universe is dominated and controlled by blackbody radiation. Assuming conservation of matter, and adiabatic expansion of radiation, then the power law in Figure 5 follows. Consider the situation at about one second into the expansion. We obtain the density of matter from the initial conditions for primordial nucleosynthesis. The density of radiation at that time depends only on universal constants, and is therefore unequivocally known. If now we have an observation at the present time of the mean density of matter, then the constancy of the above expression enables a calculation of the density of radiation, and thence the equivalent background radiation temperature. Using the present matter density suggested by Hubble in the late 1940s, we got about 5°K. Using more contemporary values of the matter density gives a background temperature compatible with the COBE results. It is unfortunately so that aside from the several publications in which Herman and described our results, Gamow went on to describe an approach in which he erroneously extrapolated approximations for early matter and radiation densities to the present time. Prior to 1965 there were eight publications on background radiation by Herman and me, and by Gamow, so that there was a rich supply of remarks in the literature. All of this was pretty well ignored by physicists and astronomers before 1965, except for some published work by Zel'dovich as well as Doroshkevich and Novikov in the Soviet Union, who referred to some of these calculations and suggested the utility of measurements from artificial satellites. Zel'dovich misinterpreted some observations made by E.A. Ohm at the Bell Telephone Laboratories as limiting any background radiation from the cosmos to less than 1°K. Herman, Follin and I made a number of attempts from 1949 to 1955 to interest other physicists and radio astronomers in looking for a background radiation. In retrospect it should have been possible with existing technology, but we found no buyers. Even Gamow got in the act, for then-student Joseph Weber (later well known for his attempts to detect gravitational waves) was told that looking for the microwave background would be fruitless.

The year 1965 was a pivotal year for this subject, for Arno Penzias and Robert Wilson of Bell Telephone Laboratories reported observing a cosmic microwave background radiation at 7.3 cm corresponding to a temperature of about 3.5°K. They were not aware of our prior prediction or of the cosmological interpretation; their work was interpreted by a group including Dicke, Peebles, Roll and Willkinson at Princeton as the relict radiation from a primeval fireball (the Big Bang). The Princeton group had been setting up a Dicke radiometer to seek residual radiation from prior collapse of an oscillating cosmological model. They were able to verify quickly the work from the Bell Laboratories, and thus began a long series of observations by many scientists verifying the reality of this cosmic microwave background. This all culminated in the stunning observations over a period of several years by the COBE satellite, launched in 1989, of a nearly perfect Planck radiation distribution corres ponding to a temperature of 2.726°K, shown as Figure 7.

The back-to-back papers by Penzias and Wilson, and by the Princeton group, appeared in Astrophysical Journal in 1965 with no reference to the prior calculations by Herman and me. The only reference to our work or Gamow's work on the background radiation made in early Princeton papers was to the Alpher-Follin-Herman paper on conditions early in the universe. The more-than-eight references to the background were not listed.

I would remind you of several other COBE observations, namely confirmation of the motion of the observing system with respect to the surface of last scattering of the microwave background radiation, which puts a dipole component in the celestial background temperature data, measurable at an amplitude of several millikelvin. There are also small departures from uniformity in the background, at a level of about 10 parts per million, which appear to be residual fluctuations from the very early universe. These departures were a welcome observation, since they provide seeds for the later formation of structure in the expansion. These matters are outside the scope of this talk.

I want to comment briefly on a number of events associated with the microwave background, including observations prior to the Penzias-Wilson announcement, and the manner in which our prior work was ignored.

In 1940 and 1942, W.S. Adams of Mt. Wilson and A. McKellar of Dominion Astrophysical Observatory published observations in which they proposed a background radiation bath at about 2.3°K based on the occupation numbers of excited rotational states with assumed oscillator strengths of the CN molecule along the line of sight to the star ζ Ophiuchi. G. Herzberg mentioned these results later in his book on molecular spectra, with the comment that of course we do not understand their origin. The result was resurrected after the Penzias-Wilson publication, principally by N. Woolf and G. Field, who had knowledge of the observations, but lacked oscillator strength data to aid in interpretation. During the 1950s there were observations by Shmaonov in the Soviet Union, and by LeRoux in France, both of whom used captured German radar antennas to observe a background of several degrees Kelvin. There was no interpretation of the results, no cosmological connection, and I have seen no critique of their work. Finally, in the notebooks of a radio astronomer named William K. Rose, then at the Naval Research Laboratory, and now at the University of Maryland, there is a report of observation of a background radiation of 2.5–3°K, using an heterodyne receiver with a maser amplifier. The work was done in 1962, but Stephen Brush, science historian, has told me that Rose did not have an opportunity to verify his result, and did not publish. When informed years later, Penzias commented that the correction for a 15°K system background was questionable.

I will not comment in detail on the rocky road traveled by our work on primordial nucleosynthesis and particularly our CMBR prediction. In retrospect I still find it hard to believe most of happened. It gave us a jaundiced view of the level of scholarship exhibited by too many people. Herman and I, and occasionally Gamow, were torn between doing nothing, as the gentlemanly course, writing mild letters of protest, and on occasion sending strongly worded protests. However, our work now seems to have been widely accepted and recognized, for which we are grateful indeed.

Shortly before Gamow passed away, at his instigation he, Herman and I coauthored a paper (1967) trying to set straight the record of our involvement in cosmological matters. It appeared in the Proceedings of the National Academy of Sciences, which, as it turns out, is the wrong place to publish if the work is something you hope people will see.

In any event, I am pleased to have been allowed this time to go over the history of the Big Bang model, and of the role played by Herman, Gamow and me. I am sorry that I could not be at this meeting to express my personal thanks for my interactions with George Gamow and Robert Herman. They were fun while they lasted, which was not long enough.

Recommended reading list

(Admittedly incomplete)

Material with considerable technical content.

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Hetherington N.S. (Ed.) *Encyclopedia of Cosmology* (Garland Publishing Co., New York, 1993)

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Peebles P.J.E. *Principles of Physical Cosmology* (Princeton University Press, Princeton, New Jersey, 1993)

Sandage A.R., Kron R.G. and Longair M.S. (Contributors; edited by B.Binggeli and R.Buser) *The Deep Universe* (Springer-Verlag, Berlin, 1995)

Tolman R.C. *Relativity, Thermodynamics and Cosmology* (Clarendon Press, Oxford, 1934)

Weinberg S. *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity* (John Wiley & Sons, New York, 1972)

Books of More General Interest

Alpher R.A., Herman R. *Genesis of the Big Bang* (Oxford University Press), 2000 (in preparation)

Bartusiak M. *Thursday's Universe* (Times Books, New York, 1986

Bartusiak M. *Through a Universe - Darkly* (Harper Collins, New York, 1993

Chaisson E. *Cosmic Dawn: The Origins of Matter and Life* (W.W.Norton & Co., New York, 1981

Chown M. *Afterglow of Creation* (University Science Books, Sausalito, California, 1996

Ferris T. *The Whole Shebang: A State-of-the-Universe(s) Report* (Simon and Schuster, New York, 1997

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