

History of Big Bang Cosmology, Part 4: The Expanding Universe, Ylem, and the CMBR

I. Introduction

This article continues our brief history of big bang cosmology[1-3] with an overview of the predictions of the expansion of the universe and the cosmic microwave background radiation.

Albert Einstein started modern cosmology with his 1917 paper that applied general relativity (GR) to the entire universe.[4] To resolve the problem at infinity that long plagued Newtonian cosmology, Einstein abolished infinity by modeling the universe as a uniform distribution of stars in a spherical space closing back on itself (positive curvature). To obtain a static solution, he also had to introduce the cosmological constant $\Lambda > 0$, which, in effect, canceled at the cosmic scale the gravitation of matter. That same year Wilhelm de Sitter found an alternative closed static solution that required the cosmological constant but contained no matter![5] For a light source at radial coordinate r relative to an observer at the origin, the “de Sitter effect” gave a fractional change in wavelength $\Delta\lambda/\lambda \sim \frac{1}{3}\Lambda r^2 (1 - \frac{1}{3}\Lambda r^2)^{-1}$. This was not a Doppler effect, although it was often interpreted as one; rather, the meterstick to measure wavelength gets altered. de Sitter’s model had curvature and cosmic redshifts without matter; Einstein’s model had curvature and matter without cosmic redshifts. The real universe has matter *and* redshifts. Between 1917 and about 1930, the argument was over which of these two models best fit the real universe. Even Edwin Hubble, who in 1929 published the first installment of data that showed the universe to be expanding, first interpreted his results as evidence for de Sitter redshifts.[6,7]

Tentative steps towards loosening the rigidities of a static universe were taken by Comas Lanzcos (1922), Georges Lemaître (1925), and H.P. Robertson (1928), who performed coordinate transformations on the de Sitter metric, shifting some time-dependence into the coefficients of the spatial displacements. [8] But new dynamical thinking came from Russia, in the person of Alexander A. Friedmann. In 1922 and 1924 he published two revolutionary papers. The first showed how GR allowed a closed universe to have a time-dependent radius.[9] The 1924 paper showed that Einstein’s equations also allowed an “open” hyperbolic (negative curvature) universe.[10] Unfortunately, Friedmann’s work went unnoticed at that time. Even more sadly, he never lived to see his ideas vindicated, as he passed away from typhoid in 1925.[11]

In 1924 the young Abbé Georges Lemaître from Belgium was visiting MIT after studying physics at Cambridge under Sir Arthur Eddington. While in America Lemaitre attended a meeting of the National Academy of Sciences in Washington, DC. There he heard Hubble present his results on measuring the distance to the Andromeda galaxy. Lemaître returned to Belgium

inspired and in 1927 independently rediscovered Friedmann’s dynamic universe.[12]

At a meeting of the Royal Astronomical Society in 1930, “de Sitter propounded the dilemma that the actual universe apparently contained enough matter to make it an Einstein world and enough motion to make it a de Sitter world.”[13] About this Arthur Eddington insightfully reflected, “One puzzling question is why there should be only two solutions. I suppose the trouble is that people look for static solutions.”[14] Lemaître read these remarks and sent Eddington a copy of his 1927 paper on an expanding universe. Upon seeing it, Eddington wrote to de Sitter:

“...it was the report of your remarks and mine at the [Royal Astronomical Society] which caused Lemaître to write me about it...A research student [G.C.] McVittie and I had been worrying at the problem and made considerable progress; so it was a blow to us to find it done much more completely by Lemaître (a blow softened, as far as I am concerned, by the fact that Lemaître was a student of mine).”[15]

In 1932 the Friedman-Lemaître metric was derived with enhanced rigor by H.P. Robertson and A.G. Walker. Today the “FLRW metric” forms the working tool of modern cosmological discussion.[16] Its implications for the expansion of the universe occupies Section II.

When the evidence became convincing that the universe *really is* expanding, Lemaître was one of the first to take seriously the implication that, very early in cosmic history, all the mass-energy within the observable universe would have been compressed into a space rescaled to diminutive size. After the neutron was discovered by James Chadwick in 1932, a large piece of the nuclear puzzle fell into place, which released a brake on attempts to understand the origin of the elements. The synthesis of nuclei in stars began to be understood, but it was realized that some prestellar nucleosynthesis must have occurred.[17] Thereby was attention brought to the very early expanding universe as an environment of sufficiently high temperature and density to drive some prestellar synthesis. In Section III we consider the thoughts of those who first tried to understand this environment and its processes, among them S. Chandrasekhar, George Gamow, Ralph Alpher, and Robert Herman. Alpher and Herman predicted the existence and present temperature of the CMBR, the definitive signature of a universe that began with a “hot big bang.”

II. An Expanding Universe

In special relativity the time interval dt and the space interval ds between two events are not separately invariant among inertial

reference frames, but the difference in their squares, the “space-time interval,” is invariant and equals the square of the *proper* time $d\tau$ between the events, $d\tau^2 = dt^2 - ds^2$ (absorbing c into t to measure time in meters). GR allows transformations among *accelerated* frames. Thanks to the equivalence principle for gravitational and inertial mass, GR offers a theory of gravity. In terms of four space-time coordinates x^μ , the space-time interval between a pair of neighboring events may be written in general as

$$d\tau^2 = g_{\mu\nu} dx^\mu dx^\nu \quad (1)$$

(sum over repeated indices), where the coefficients $g_{\mu\nu}$ denote components of the metric tensor (or matrix) that converts coordinate displacements into distances. Given a distribution of mass-energy as the source of the gravitational field, Einstein’s field equations of GR are second-order partial differential equations that one solves for $g_{\mu\nu}$. The mass-energy information is encoded into another matrix $T_{\mu\nu}$, whose components include energy density and pressure terms. The cosmological constant Λ serves as another gravitational source. The field equations take the schematic form

$$[g(\partial g) + \partial^2 g \text{ terms}]_{\mu\nu} = -8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}, \quad (2)$$

where G denotes Newton’s gravitational constant.

Alexander Friedmann was attracted to the mathematical challenges of GR. His 1922 cosmology paper bears the modest title “On the curvature of space,” but the subject was dynamics.[9] Like Einstein and de Sitter, he considered universe filled with uniform densities of matter and radiation, in a closed, spherical geometry, with three-dimensional space conceptualized as the surface of a hypersphere of radius a embedded in a Euclidean space of four dimensions. But unlike his predecessors, Friedmann allowed a to vary with time. In 1923 he also applied Lobachevskian geometry, spaces of negative curvature, to GR. The resulting paper, called “On the possibility of a world with constant negative curvature,” was published in 1924.[10] Here one imagines three-dimensional space as a hyperbolic surface embedded in four-dimensional Euclidian space.

The closed and open geometries may be parameterized, for homogeneous and isotropic space, as

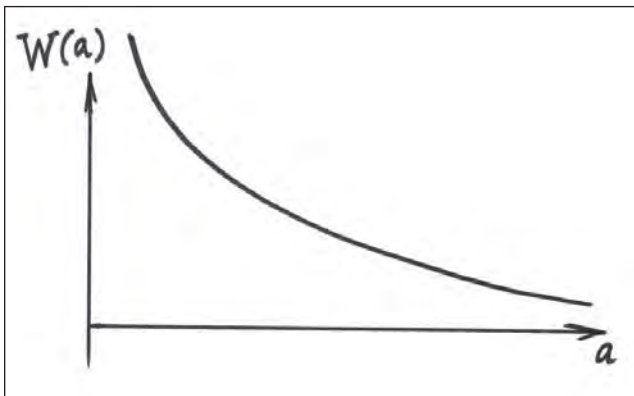


Fig. 1. $W(a)$ in the open universe model. As a increases from 0, W begins from a singularity, going asymptotically to 0 as $a \rightarrow \infty$.

$$d\tau^2 = dt^2 - a^2 [(1 - kr^2)^{-1} dr^2 - r^2(d\theta^2 + \sin^2\theta d\phi^2)], \quad (3)$$

where (r, θ, ϕ) denote familiar spherical coordinates. The parameter $a = a(t)$ allows space to be rescaled as time t elapses; r has been normalized to a dimensionless coordinate-grid label; and $k = +1$ (-1) for the closed (open) universe, with $k = 0$ for no-curvature “flat” geometry.

With the mass-energy distribution of matter and radiation modeled as a smoothed-out energy density $\rho = \rho_{\text{mat}} + \rho_{\text{rad}}$ and an equation of state relating pressure P to ρ , the field equations of GR may be written as a pair equations for the evolution of $a(t)$:

$$(da/dt)^2 = \kappa\rho a^2 + \frac{1}{3}\Lambda a^2 - k \quad (4)$$

and

$$d^2a/dt^2 = -\frac{1}{2}\kappa(\rho + 3P)a + \frac{1}{3}\Lambda a, \quad (5)$$

where $\kappa \equiv 8\pi G/3$.

The study of $a(t)$ now forms our task. If $a(t)$ begins from zero, in that first instant it expands infinitely fast from a state of infinite energy density. Friedmann’s biographers observe, “The discovery of the initial singularity is one of the most remarkable achievements of Friedmann’s theory...”[18] The subsequent expansion is described by well-behaved functions. At small values of a in the early expansion, $1/a$ dominates over other terms and the equations integrate to a power law, $a(t) \sim t^{2/3}$. If the universe continues to expand, $a(t)$ swells so large that the universe approaches a state of vanishing energy density and exponential growth, $a(t) \sim e^{1/3\Lambda t}$.

To examine the more nuanced behavior of $a(t)$, transpose Eq. (4) into an expression for da/dt . For the closed universe,

$$da/dt = \pm (\sqrt{1/3}) a [\Lambda - Q(a)]^{1/2}, \quad (6)$$

where

$$Q(a) \equiv (3/a^3)(a - a_1) \quad (7)$$

and $a_1 \equiv \kappa\rho a^3$, which is constant by conservation of energy. For

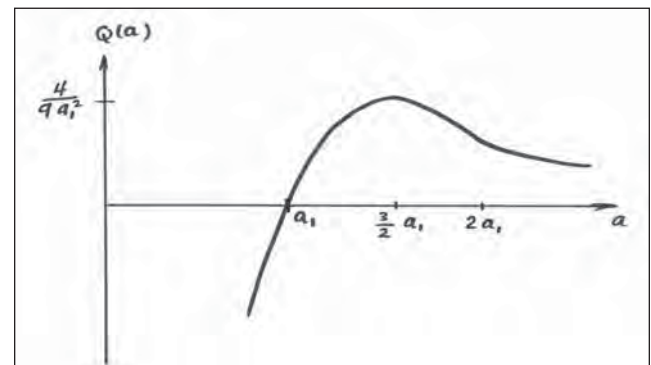


Fig. 2. Graph of $Q(a)$ showing its asymptotic behavior as $a \rightarrow 0$ and as $a \rightarrow \infty$. A zero of Q occurs at $a = a_1$, its maximum at $a = 3a_1/2$, and an inflection point at $a = 2a_1$.

the open universe,

$$da/dt = \pm (\sqrt{1/3}) a [\Lambda + W(a)]^{1/2} \quad (8)$$

where

$$W(a) \equiv (3/a^3)(a + a_1). \quad (9)$$

Sketches of $W(a)$ and $Q(a)$ appear in Figs. 1 and 2.

In an open universe, W exhibits no maximum or minimum, and the open universe expands forever. However, a closed universe offers other possibilities. For da/dt to be real, Eq. (6) demands $\Lambda \geq Q(a)$, where $Q_{\max} = 4/9a_1^2$. Consider three cases:

(a) $\Lambda > Q_{\max}$. From Eq. (6) we find that da/dt remains a real number for all values of a . The universe expands monotonically while experiencing gravitational deceleration from $a = 0$ to $a = 2a_1$. When $a > 2a_1$ the expansion accelerates with positive sign as the cosmological constant dominates over energy density.

(b) If $\Lambda = Q_{\max}$ precisely, then as a grows from zero it decelerates until reaching $a = 3a_1/2$, where the expansion halts. The static Einstein universe, contained in the Friedmann model as a special case, may now be recognized as unstable, poised between collapse and runaway expansion on a precarious peak at $a = 3a_1/2$.

(c) If $0 \leq \Lambda < Q_{\max}$, a turning point occurs when $Q(a) = \Lambda$, which puts a turning point a_1 in the range $a_1 \leq a_T < 3a_1/2$. Because $d^2Q/da^2 < 0$ in this region, upon hitting the turning point the expansion halts and the universe begins to contract, ultimately into another singularity. The simplest such case occurs when $\Lambda = 0$. Defining $d\alpha \equiv dt/a(t)$, a parametric solution of a cycloid results:[19]

$$a = \frac{1}{2}a_0 (1 - \cos \alpha), \quad t = \frac{1}{2}a_0 (\alpha - \sin \alpha), \quad (10)$$

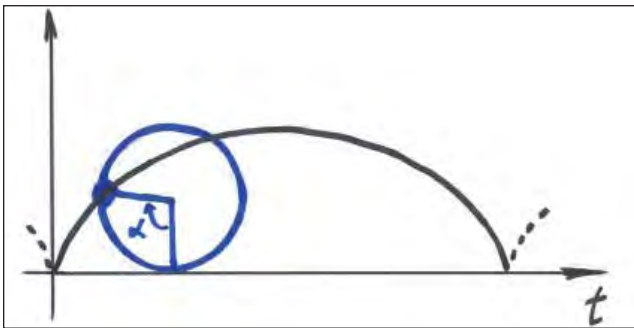


Fig. 3. The expansion and re-contraction of the closed, perhaps oscillating, universe.

describing the trajectory of Fig. 3, with period $T = a_1\pi$ for the entire cycle. Perhaps the cycle repeats from infinite past and into an infinite future (but that raises difficulties with Second Law of Thermodynamics).

The expansion carries apart any two points A and B located

at fixed *coordinates*. Even when A and B do not move *through* space they are carried apart, at a rate proportional to their separation, by the *stretching* of space. The FLRW model predicts a velocity-distance relation. From the space time interval, the *distance* s between events 1 and 2 at fixed *coordinates* r_1 and r_2 on a radial line is

$$s = a(t) \int_{r_1}^{r_2} (1 - kr^2)^{-1/2} dr, \quad (11)$$

which increases at the rate $v \equiv ds/dt = (da/dt) s/a$. If we define the parameter

$$H(t) \equiv (1/a) (da/dt) = [(8\pi G/3)\rho - k/a^2 + 1/3\Lambda]^{1/2}, \quad (12)$$

then we have the “velocity-distance relation,”

$$v = Hs. \quad (13)$$

When current values of the parameters are used, Eq. (13) is called “Hubble’s Law.” The velocity-distance relation means that *space itself* gets rescaled. (Galaxies and people do not expand, because they are held together by their internal forces.)

III. Ylem and the CMBR

When the data on the velocity-distance relation became robust enough to convince everyone that the universe *really expands*, Lemaître took seriously the inferences. Thereby did cosmology take the next step beyond dynamic geometry, to early-universe thermodynamics and nuclear physics. Since the universe expands now, it must have existed at smaller scales in the past. When $a(t)$ was very small, the universe would have been astonishingly dense. Since the largest density known to exist was nuclear matter, Lemaître suggested the state of matter in the early universe

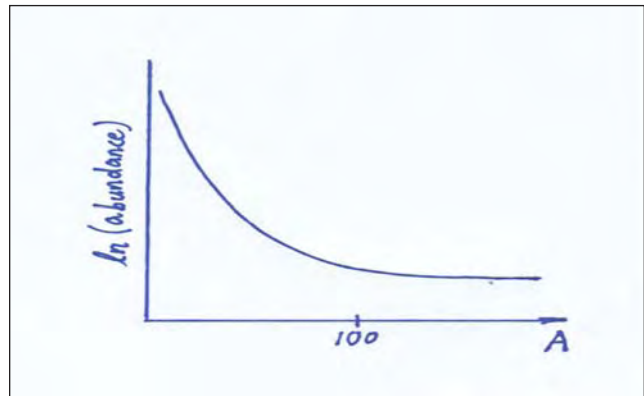


Fig. 4. Schematic smoothed-out plot of the logarithm of relative abundance vs. mass number $A =$ number of protons plus neutrons. The curve is approximately exponential out to about $A \approx 100$ and constant thereafter.

may have been a giant nucleus, a “primaeval atom” or “cosmic egg.” As the expansion began, the cosmic forces *were* local, stretching the primordial nucleus apart, eventually onto “our poor little atoms.”[20] Lemaître sought in this scenario an explanation for high-energy cosmic rays.

By the 1930s the relative abundances of the various nuclear species and their isotopes were known (see Fig. 4), and that distribution was apparently universal across the observable cosmos.

It was also known that these abundances could not be accounted for entirely by nuclear reactions in stars,[17] suggesting a prestellar episode of element production in cosmic history. This discussion requires a small digression into early-universe thermodynamics. Let's do some back-of-the-envelope calculations here.

By differentiating Eq. (4) with respect to time and neglecting Λ (which is small anyway, and negligible in the early universe) and using Eq. (5) we derive

$$d(\rho a^3) = -3Pa^2 da. \quad (14)$$

Because ρ denotes energy density and because the volume V of the universe is proportional to a^3 , the term ρa^3 represents the "internal energy" U of the universe. Thus Eq. (14) may be written $dU = -P dV$, which resembles the combined 1st and 2nd laws of thermodynamics, $dU = TdS - PdV$, but without the entropy S . So in the early universe, entropy is conserved, $dS/dt = 0$. One may calculate S from its usual definition:

$$S = \int (dU + PdV) / T \sim (\rho + P) a^3 / T, \quad (15)$$

where we take the state variables to be spatially uniform, in keeping with the assumption of homogeneity and isotropy. Equation (15) enables us to relate a to the temperature. In the very early universe, all the particles move at practically the speed of light. Therefore, like the photon, their energy densities and pressures are proportional to T^4 (Stefan's law). Then from Eq. (15), it follows that $S \sim T^3 a^3$, but $S = const.$, so the universe expands and cools adiabatically according to $T = b/a$, where b is some constant. To eliminate b we find the temperature T as a function of time t . From Stefan's law we have $P \sim \rho = \sigma T^4 = \sigma b^4/a^4$ (σ denotes the Stefan's law constant, weighted by spin multiplicities). When placed into Eq. (4) without Λ , this yields

$$(da/dt)^2 + k = (\mu/a)^2 \quad (16)$$

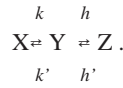
where $\mu^2 = \kappa\sigma b^4$. At early times when a is small the $1/a^2$ term dominates over k , so that $da/dt \approx \mu/a$, with solution $a^2 = 2\mu t$. Since $a = b/T$, the b cancels, and we find

$$T^2 t \approx 1.9 \times 10^{20} \text{ K}^2 \text{ s}. \quad (17)$$

(The 1.9 coefficient is faithful to my little calculation here; other authors always get something near 2).[21]

If one imagines the prestellar universe to be a gas of neutrons and protons (transforming into one another by beta decay and its inverse), with an increasing contamination of nuclei made by their collisions, and if during those high-temperature collisions the nuclear species are in "chemical" equilibrium with one another, then when the temperature drops to the point where fusion no longer occurs, those reactions cease and the abundance ratios of that moment would be "frozen" in. This idea was developed with great thoroughness by S. Chandrasekhar and Louis R.

Henrich in 1942.[22] They carried out a complex problem whose strategy may be illustrated with a toy model. Consider elements X, Y, and Z that can change into one another as follows:



The rate at which the concentration $[X]$ of species X decays to Y is proportional to the concentration of $[X]$, with some coefficient k , and the rate at which X gets made from Y depends on the concentration $[Y]$, with some coefficient k' . Therefore we may write

$$d[X]/dt = -k[X] + k' [Y]. \quad (18)$$

Including the other transformations between Y and Z with rate coefficients h and h' , we write

$$d[Y]/dt = -(k' + h)[Y] + k [X] + h' [Z] \quad (19)$$

$$d[Z]/dt = -h' [Z] + h [Y]. \quad (20)$$

In equilibrium, $d[X]/dt = d[Y]/dt = d[Z]/dt = 0$, and we find $[Y]/[X] = k/k'$ and $[Z]/[X] = kh/k'h'$. If the coefficients are known functions of temperature, and the temperature a known function of time, and if the present abundances are the "frozen in" values they had when the reactions were suddenly quenched, then from the observed abundances we can find the time and temperature of that quenching. Invariably the Boltzmann factor makes an appearance, so that $[Y]/[X]$ or $[Z]/[X] \sim \exp(-\Delta mc^2/k_B T)$, where Δm is the mass defect (or binding energy) and k_B Boltzmann's constant. If the time and temperature of the quenching can be found by fitting to a known abundance, the rest can be predicted.

This program agreed well with the exponential decline for about the first half of the periodic table, but for the second half, where the actual abundance levels off, the predictions continue their exponential decline. By 1946 George Gamow was suggesting in a series of talks and papers that "it appears that the only way of explaining the observed abundance-curve lies in the assumption of some kind of unequilibrium process taking place during a limited interval of time." [23]

Gamow had tremendous intuition and physical insight, but mathematical patience for complex calculations was not his primary strength. Therefore when his graduate student Ralph A. Alpher was in need of a second PhD dissertation topic,[24] he took on the task of predicting the abundances of the elements in the complicated, out-of-equilibrium dynamics of the high-temperature environment in the early universe.

This good work resulted in a series of papers by Alpher and his colleagues over the next several years. The first to emerge from the dissertation was published in *Physical Review* in April 1948, bearing the title "The Origin of Chemical Elements." [25] Gamow, an irredeemable prankster, could not resist the temptation to put the name of Hans Bethe on the paper, called to this day the " $\alpha\beta\gamma$ paper."

Our Greek-letter authors wrote, "According to this picture, we must imagine the early state of matter as a highly compressed neutron gas (overheated nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as

the result of universal expansion. The radiative capture of the still-remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei.” For nuclear species $i = 1, 2, 3, \dots, 238$ denoting all the nuclei with mass number $i = A$ out to uranium (the various isotopes for common A emerging later from beta decays), the rate equations for this building-up process (neglecting fissions) are of the form

$$dn_i/dt = f(t) [\sigma_{i-1} n_{i-1} - \sigma_i n_i], \quad (21)$$

where $f(t)$ carries the time-dependent factors, n_i denotes the particle density of species i , and σ_i denotes its cross-section for neutron absorption (recall the cross-section is the area, centered on the target nucleus, within which the neutron must hit to make the reaction go). Given the rapidity of the reactions compared to the neutron half-life, $\alpha\beta\gamma$ assumed the nuclear reactions went to completion in a time short enough that the expansion was negligible during those moments. Upon integrating the coupled rate equations, our authors found that the curve of relative abundances could be fit, for essentially all the elements, with a common value of $\rho_n \Delta t = 5 \times 10^4 \text{ g s/cm}^3$, the product of neutron density and time interval during which the element buildup occurred. Alpher’s calculations showed the process of element-building by neutron capture to be essentially finished when $t \approx 5 \text{ min}$.

These calculations were explained in more detail in a longer paper written by Alpher alone later that year, “A Neutron-Capture Theory of the Formation and Relative Abundance of the Elements.”[26] Into this discussion Alpher introduced the antique word *ylem*, pronounced $\text{ˈ}i\text{-}l\text{ə}m$, the primordial stuff from which



Fig. 5. Robert Herman (L) and Ralph Alpher (R) witness George Gamow emerge from a bottle of ylem. This slide was sneaked into a stack for a talk that Gamow presented. He saw it first when it flashed boldly on the screen. Alpher noted the bottle’s “contents were partially consumed by those in the photo to celebrate the mailing of the Alpher-Bethe-Gamow paper to *Physical Review* in 1948.” Photo courtesy of Victor Alpher.

all matter condensed (see Fig. 5). Alpher noted, “According to Webster’s New International Dictionary, 2nd ed., the word ‘ylem’ is an obsolete noun meaning ‘The primordial substance from which the elements were formed.’ It seems highly desirable that a word of so appropriate a meaning be resurrected.” Yes, it should—and perhaps it has. My American Heritage College Dictionary defines *ylem* as “A form of matter hypothesized by proponents of the big bang theory to have existed before the formation of the chemical elements.” In Alpher’s models of 1948, the ylem was a liqueur of very hot neutrons that became enriched with protons, electrons, neutrinos, and heavier elements during the first five minutes of the expansion.

Further refinements formed the subject of another 1948 paper, written by Alpher and his colleague from the Johns Hopkins Applied Physics Lab, Robert Herman, who had studied relativity at Princeton under H.P. Robertson. (It should be noted that Alpher and Herman did cosmology *after* their day jobs of mostly classified defense-related work on topics like the hydrodynamics of missile re-entry into Earth’s atmosphere.) Their first joint paper, “On the Relative Abundance of the Elements,” included the effects of the expansion during nucleosynthesis, and the beta decays.[27] It was one of their first co-published results in what would prove to be a half-century collaboration and lifetime friendship.[28]

In the summer of 1948 while he was at Los Alamos, George Gamow wrote a hasty paper called “The Evolution of the Universe” that attempted to connect nucleosynthesis criteria to the formation of galaxies by gravitational condensation.[29] He mailed the paper to *Nature* and sent a copy to Alpher and Herman. They scrutinized his work, noticed some minor errors, and informed him of them. Gamow replied that it was too late to change his paper, which was already in *Nature*’s publication pipeline, but he asked the journal editors to watch for Alpher and Herman’s forthcoming corrections and publish them as soon as possible.

Gamow’s paper appeared in the October 30 issue and the Alpher- Herman corrections appeared on November 13, the latter in a short but significant article also called “Evolution of the Universe.” At issue in Gamow’s paper, and corrected by Alpher and Herman, was the “cross-over time,” when the energy densities of matter and radiation became equal, a necessary condition for galaxies to form. After noting these corrections, Alpher and Herman remarked that, according to their thermodynamic calculations, “The temperature of the gas at the time of condensation was 600°K, and the temperature of the universe at the present time is found to be about 5°K. We hope to publish the details of these calculations in the near future.”[30]

Those details appeared in the *Physical Review* the following April as another article by Alpher and Herman, called “Remarks on the Evolution of the Expanding Universe.”[31] Our authors considered “an expanding universe of non-interconverting matter and radiation,” after matter-radiation decoupling when their energy densities became *separately* conserved. The conservation of matter gives $\rho_m a^3 = \text{const}$. If the radiation energy density is given by a Planck blackbody spectrum, $\rho_r \sim T^4$, and an adiabatic expansion where $T \sim 1/a$, one has $\rho_r a^4 = \text{const}$. Putting these together, it follows that

$$\rho_m \rho_r^{-4/3} = \text{const.} \quad (21)$$

Using primes to denote “then” as the time of element formation in the early universe, and double primes to denote “now,” Alpher and Herman calculated that “the specification of $\rho_{m'}$, $\rho_{m''}$, and $\rho_{r'}$ fixes the present density of radiation, ρ_r . In fact, we find that the value of $\rho_{r'}$, consistent with Eq. (4) [our Eq. (21)], is

$$\rho_{r'} \approx 10^{-32} \text{ g/cm}^3,$$

which corresponds to a temperature now of the order of 5°K . This mean temperature for the universe is to be interpreted as the background temperature which would result from the universal expansion alone.”

Radiation at a temperature of a few Kelvins means that the cosmic afterglow of the big bang would exhibit a Planck spectrum peaked in the microwave part of the spectrum. Thus was the existence and temperature of the cosmic microwave background radiation (CMBR) predicted by Alpher and Herman in 1948 and 1949.

Throughout the balance of the 1940s and through the 1950s, they attempted to convince radio astronomers to search for this relic radiation, to no avail. However, it seems to have been detected (but not recognized as the CMBR) in the early 1940s,[32] and discovered (and recognized) in the USSR in 1957. [33] Few noticed.

In late 1964, A. Penzias and R. Wilson serendipitously detected an unaccounted-for 3 K temperature excess in their microwave antenna.[34] The Princeton group of R.H. Dicke, P.J.E. Peeble, P.G. Roll, and D.T. Wilkinson interpreted the discovery as a CMBR.[35] Neither one of these papers cited the CMBR prediction of Alpher and Herman, and until recent years few seemed to recall the Alpher-Herman prediction of the CMBR at all. Over the years, the error of citing Gamow or “Gamow and his students” as the original author of the CMBR prediction has been propagated.

This unfortunate circumstance put Ralph Alpher and Robert Herman in the distinguished cosmological company of Alexander Friedmann and Georges Lemaître. As in their cases, the overdue record of priority is slowly being set straight.[36-39] The detection of the CMBR, whose existence was predicted by Alpher and Herman, was the cinching link between theory and evidence that compelled the astrophysics community to take the hot big bang seriously. Friedmann and Lemaître “made the universe expand,” and Alpher and Hermann made it glow.

Acknowledgments

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- [18] Tropp, Frenkel, Chernin, ref. 11, p. 158.
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- [21] B. Eskridge and D.E. Neuenschwander, “A Pedagogical Model of Primordial Helium Synthesis,” *Am. J. Phys.* **64**, 1517-1524 (1996).
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- [23] G. Gamow, “Concerning the Origin of Chemical Elements,” *J. Wash. Acad. Sci.* **32**, 353-373 (1942); “Expanding Universe and the Origin of Elements,” *Phys. Rev.* **70**, 572-573 (1946).
- [24] Alpher had almost completed a dissertation on galaxy formation when he was “scooped” by E. Lifchitz. See the biographical article by Victor Alpher that begins on p. 15 of this issue of *Radiations*.
- [25] R.A. Alpher, H. Bethe, and G. Gamow, “The Origin of Chemical Elements,” *Phys. Rev.* **73**, 803-804 (1948).
- [26] R. Alpher, “A Neutron-Capture Theory of the Formation and Relative Abundance of the Elements,” *Phys. Rev.* **74**, 1577-1589 (1948).

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[28] Their papers from this era on these subjects, authored separately or jointly by Alpher, Gamow, Herman, and Follin, are not listed in their entirety here. We plead lack of space.

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[31] R. Alpher and R. Herman, "Remarks on the Evolution of the Expanding Universe," *Phys. Rev.* **75**, 1089-1095 (1949).

[32] W.S. Adams, "Some Results with the Coudé Spectrograph of the Mount Wilson Observatory," *Ast. J.*, **93**, 11-23 (1941). A. McKellar, "Evidence for the Molecular Origin of Some Hitherto Unidentified Interstellar Lines," *Pub. Ast. Soc. Pacific*, **52**, 307, 187-192 1940; **53** 233-235 (1941).

[33] I.D. Novikov, *Black Holes and the Universe*, V. Kisin, Tr.

(Cambridge Univ. Pr., 1984).

[34] A. Penzias and R. Wilson, "A Measurement of Excess Antenna Temperature at 4080 Mc/s," *Astrophys. J.* **142**, 419-421 (1965).

[35] R.H. Dicke, P.J.E. Peebles, P.G. Roll, and D.T. Wilkinson, "Cosmic Black-Body Radiation," *Astrophys. J.* **142**, 414-419 (1965).

[36] M.S. Turner, "From $\alpha\beta\gamma$ to Precision Cosmology: The Amazing Legacy of a Wrong Paper," *Physics Today*, **61**, Dec 2008. The $\alpha\beta\gamma$ was "wrong" for all the right reasons.

[37] "April 1, 1948: The alpha beta gamma paper explains the origin of the elements," *APS News*, April 2008, p. 2.

[38] R. Alpher and R. Herman, "Reflections of Early Work on 'Big Bang' Cosmology," *Physics Today* **41**, 24-34 (Aug 1988).

[39] R. Alpher and R. Herman, *Genesis of the Big Bang* (Oxford Univ. Pr., 2001).

Student Congress Perspectives continued from page 7

Bringing it Home

By the Kansas University SPS chapter

[W]e used our next SPS meeting to have a roundtable discussion following up on topics from the conference. We shared with each other and with those unable to attend the Congress the interesting things we had heard and seen on our tours. We also discussed some of the issues that the conference addressed, and what initiatives we felt we could practically pursue as a campus chapter. Among other things, we are hoping to establish a connection with students interested in science at the Native American university in our town and open a dialogue there.



The Congress brought together students, faculty, and alumni from over 170 campuses and institutions across the country. Our hope is that they continue the discussion of scientific citizenship back home with their colleagues and friends, and in this way move the physics community forward.

Photo by Matt Noll.

Seeing the Possibilities

By the Abilene Christian University SPS chapter

Overall the conference broadened our horizons on what is truly possible in the field of physics.

The conference allowed all of us to look outside of our own personal experience as physicists, be it as students, researchers, or teachers, and view things from a more national and global perspective. It brought about reflection on what it means to live not just as a scientist, but as a citizen scientist, and imbued a sense of greater responsibility to the community that invests in us.



A view through Tractricious, a sculpture on the Fermilab grounds designed by founding director Robert R. Wilson. The free-standing hyperboloid is made from unused stainless steel beam pipe.

Photo by Reidar Hahn, courtesy of Fermilab.