THE ORIGIN OF ELEMENTS

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by
ARNO A. PENZIAS
Bell Laboratories, Holmdel, N. J. USA

Throughout most of recorded history, matter was thought to be composed of various combinations of four basic elements; earth, air, fire and water. Modern science has replaced this list with a considerably longer one; the known chemical elements now number well over one hundred. Most of these, the oxygen we breathe, the iron in our blood, the uranium in our reactors, were formed during the fiery lifetimes and explosive deaths of stars in the heavens around us. A few of the elements were formed before the stars even existed, during the birth of the universe itself.

The story of how the modern understanding of the origin of the chemical elements was acquired is the subject of this review. A good place to begin is with Lavoisier who, in 1789, published the first scientific list of the elements. Five of the twenty or so elements in Lavoisier's list were due to the work of Carl Wilhelm Scheele of Köping. (He was rewarded with a pension by the same Academy to whom the present talk is adressed, more than a century before Alfred Nobel entrusted another task of scientific recognition to it.) Toward the end of the last century the systematic compilation of the elements into Mendeleev's periodic table carried with it the seeds of hope for a systematic understanding of the nature of the elements and how they came to be.

The full scientific understanding of the origin of the elements requires a description of their build-up from their common component parts (e.g., protons and neutrons) under conditions known to exist, or to have existed, in some accessible place. Thus, the quest for this understanding began with nuclear physics. Once plausible build-up processes were identified and the conditions they required were determined, the search for appropriate sites for the nuclear reactions followed. Although this search was begun in earnest in the nineteen thirties, it was only toward the end of the nineteen sixties that the full outlines of a satisfactory theoretical framework emerged. In the broad outlines of the relevant scientific thought during this period one can discern an ebb and flow between two views. In the first, the elements were thought to have been made in the stars of our galaxy and thrust back out into space to provide the raw material for, among other things, new suns, planets and the rock beneath our feet. In the second view, a hot soup of nuclear particles was supposed to have been cooked into the existing elements before the stars were formed. This pre-stellar state was generally associated with an early hot condensed stage of the expanding universe.

Historically, the first quantitative formulations of element build-up were attempted in the nineteen thirties; they were found to require conditions then thought to be unavailable in stars. As a consequence, attention turned in the 1940's to consideration of a pre-stellar state as the site of element formation. This effort was not successful in achieving its stated goal, and in the 1950's interest again turned to element formation in stars. By then the existence of a wide range of stellar conditions which had been excluded in earlier views had become accepted. Finally, the 1960's saw a reawakened interest in the idea of a pre-stellar state at the same time that decisive observational support was given to the "Big Bang" universe by the discovery of cosmic microwave background radiation and its identification as the relict radiation of the initial fireball.

Given the benefit of hindsight, it is clear that the process of understanding was severely impeded by limitations imposed by the narrow range of temperature and pressure then thought to be available for the process of nuclear build-up in stars. The theory of stellar interiors based upon classical thermodynamics (Eddington, 1926) seemed able to explain the state of the then known stars in terms of conditions not vastly different from those in our sun. The much higher temperatures and pressures suggested by the nuclear physics of element formation were thought to be possible only under conditions of irreversible collapse (i.e. the theory lacked mechanisms for withstanding the tremendous gravitational forces involved); hence no material produced under those conditions could have found its way back into the interstellar medium and ordinary stars. The arguments and mechanisms required to depict the formation of heavy elements and their ejection into space are subtle ones. In describing them, S. Chandrasekhar wrote, ". . one must have faith in drawing the consequences of the existence of the white dwarf limit. But that faith was lacking in the thirties and forties for reasons set out in my (to be published) article 'Why are the Stars as they are?." Thus, our story of a forty-year-long journey begins with the absence of sufficient faith.

The nuclear physics picture of element formation in an astrophysical setting was the subject of von Weizsäcker's "Über Elementumwandlungen im Innern der Sterne" (1937, 1938). (Interested readers can find a guide to earlier literature in Alpher and Herman's 1950 review.) The central feature of von Weizsäcker's work is a "build-up hypothesis" of neutrons and intervening β -decays; the direct build-up from protons would be blocked by the Coulomb repulsion of the positively charged nuclei of the heavier elements. Quantitative predictions that follow from this hypothesis can be obtained from the general features of empirical abundance-stability data through use of thermodynamic equilibrium relations like those used in the study of chemical reactions.

Consider the reversible exothermic reaction of two elements A and B combining to form a stable compound AB with an energy of formation ΔE, i. e.,

$$A+B \rightarrow AB+\Delta E. \qquad (1)$$

Using square brackets to indicate concentration, we can compute relative abundances at thermal equilibrium from the relation

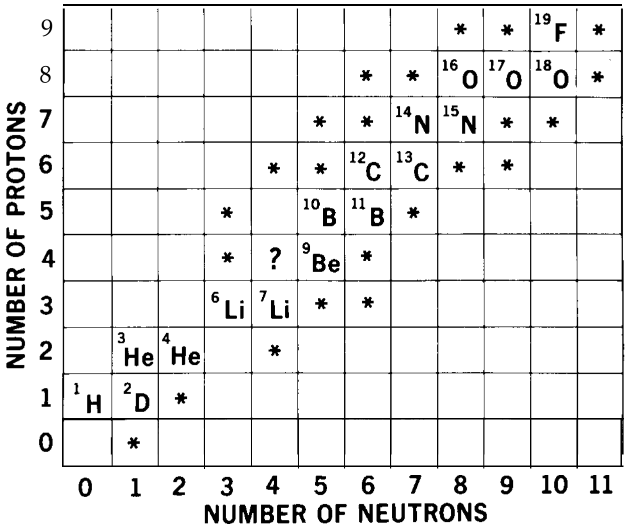
$$\frac{[A]x[B]}{[AB]} \propto exp\,(-\Delta E/kT). \tag{2}$$

where k is Boltzmann's constant.

The stable isotopes of the lighter elements have approximately equal numbers of neutrons and protons (fig. 1). The sequential addition of neutrons to a nucleus, ^{16}O say, results in heavier isotopes of the same element, ^{17}O and then ^{18}O in this case, until the imbalance of neutrons and protons is large enough to make the nucleus unstable. (^{19}O β - decays to ^{19}F in ~ 29 seconds.) A measure of the stability of an isotope is the increment in binding energy due to the last particle added. In the case of ^{17}O, for example, we have for this increment,

$$\Delta E(17) = [M(16)+M(n)-M(17)]c^2, \tag{3}$$

where M(16), M(n) and M(17) are the masses of ^{16}O, a neutron and ^{17}O, respectively, and c^2 is the square of the speed of light. In our example, the mass of ^{17}O is 17.004533 A.M.U., that of the neutron is 1.008986 and that of ^{16}O is 16.00000. Substituting in eqn (3) we find the binding energy increment to be .004453 A.M.U. or 6.7x10^{-6}ergs. We can get some idea of the temperatures involved in the addition of a neutron to ^{16}O from the use of relation (2). Because of the exponential nature of this relation, we can



	0	1	2	3	4	5	6	7	8	9	10	11
9									*	*	^{19}F	*
8							*	*	^{16}O	^{17}O	^{18}O	*
7						*	*	^{14}N	^{15}N	*	*	
6					*	*	^{12}C	^{13}C	*	*		
5				*		^{10}B	^{11}B	*				
4				*	?	^{9}Be	*					
3				^{6}Li	^{7}Li	*	*					
2		^{3}He	^{4}He		*							
1	^{1}H	^{2}D	*									
0		*										

Fig. 1 ***The Elements, Hydrogen Through Flourine.*** The stable nuclei are plotted as a function of the number of protons and neutrons they contain. Radioactive combinations are indicated by an asterisk, an empty box indicates that the corresponding combination of protons and neutrons doesn't exist. (Note that both ***mass-5*** boxes are empty.) The question mark indicates ^{8}Be; it can exist under special conditions as a metastable combination of two ^{4}He nuclei, thus providing the key stepping-stone in the transformation of three ^{4}He's into ^{12}C.

expect ΔE and kT to be of comparable magnitude for a wide range of relative isotopic abundances. Thus, from the approximation,

$$\Delta E \approx kT$$

we find that 6.7x10ergs corresponds to a temperature of 5×10^{10}K.

Following earlier workers, von Weizsäcker applied the above relations to the relative abundance of the isotopes of a given element having three stable isotopes, (^{16}O, ^{17}O and ^{18}O for example) in a state of equilibrium established by thermal contact with a bath of neutrons at temperature T. If [^{16}O], [^{17}O], [^{18}O] and [n] are the concentrations of the two oxygen nuclei and the neutrons respectively, we may use the relations (2) and (3) to write

$$\frac{[^{16}O][n]}{[^{17}O]} \propto exp\ (\Delta E(17)/kT)$$

as well as

$$\frac{[^{17}O][n]}{[^{18}O]} \propto exp\ (\Delta E(18)/kT)$$

Thus the relative abundances of the three isotopes yield a pair of expressions involving the neutron density and temperature which permit the separate determination of these two quantities from the oxygen abundance data alone. (The abundances of several hundred stable nuclei -fig. 2 - had been determined from terrestrial samples supplemented by stellar spectra and meteorites.)

Using this three-isotope method, Chandrasekhar and Henrich (1942) obtained thermal equilibrium neutron densities and temperatures for five elements. Not surprisingly, in view of previous work, each element required a different temperature and neutron density. While the range of the temperature values was relatively small, between $2.9 \times 10^{9}$for neon and $12.9 \times 10^{9}$for silicon, the neutron densities ranged from ~ 10^{31}cm^{-3}for silicon to ~ 10^{19}cm^{-3}for sulphur, some twelve orders of magnitude! The high values of the temperatures and pressures derived as well as their lack of element-to-element consistency shows the shortcomings of this thermal equilibrium picture of stellar element formation.

Another problem with this neutron build-up picture was the simultaneous requirement of very rapid neutron capture in the formation of elements such as uranium and thorium, and very slow neutron capture for the formation of others. The "slow" elements require the capture sequence of neutrons to be *slow* enough to permit intervening β-decays, while others require *rapid* sequential neutron capture in order to permit their formation from a series of short-lived nuclei. The elements formed by these slow and rapid processes correspond, respectively, to the s and r peaks of fig. 2 [A concise early discussion of this problem is presented in the final chapter of Chandrasekhar's 1939 text.]

Another approach to the element formation problem provided an enormous contribution to understanding the nuclear physics of stars. In a

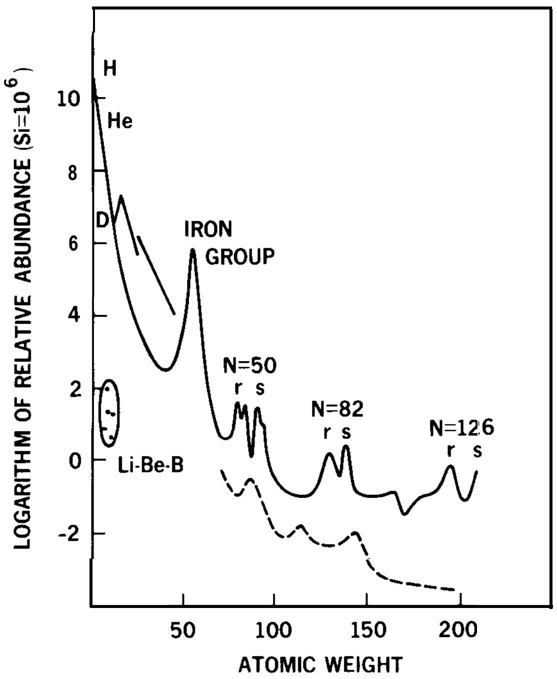


Fig. 2 ***Relative Abundances of the Elements:*** Smoothed curves representing the abundances of various groups of elements, after Burbidge et. al, 1957, who presented a total of eight processes to fit this data (See Clayton 1968 for a more modern treatment.) Lithium, Beryllium and Boron (circled) are not formed in the build-up process which goes from helium to carbon. The small amounts of these elements found in nature are fragments from the break-up of heavier elements.

beautiful paper entitled, "Energy Production in Stars", Bethe (1939) considered the individual nuclear reactions of the light nuclei, from hydrogen through oxygen. This paper established the role of the fusing of hydrogen into helium by two processes and demonstrated their quantitative agreement with observations. In the first process, protons combine to form a deuteron which is then transformed into ^{4}He by the further capture of protons. In the second, carbon and nitrogen are used as catalysts, viz

$$^{12}C+H = {}^{13}N+\gamma,\ {}^{13}N = {}^{13}C+e^{+}$$
$$^{13}C+H = {}^{14}N+\gamma$$
$$^{14}N+H = {}^{15}O+\gamma,\ {}^{15}O = {}^{15}N+e^{+}$$
$$^{15}N+H = {}^{12}C+{}^{4}He$$

(The notation and format are taken from the cited reference.)

As to the build-up of the heavier elements, however, no stable build-up process beyond the mass-4 nucleus had been found; a mass-4 nucleus cannot be combined with any other nucleus to form a heavier nucleus. In particular, no stable mass-5 nucleus exists, so the addition of a neutron or proton to ^{4}He doesn't work. Bethe wrote, "The progress of nuclear physics in the past few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars . . under present conditions, no elements heavier than helium can be built up to any appreciable extent". In an attempt to bypass the mass-4 barrier, Bethe considered, and correctly rejected, the direct formation of ^{12}C from the simultaneous collision of three helium nuclei. He also noted that the formation of ^{8}Be from two helium nuclei was prevented by the fact that this nucleus was known to be unstable, having a negative binding energy of "between 40 and 100 keV". This energy difference corresponds to a temperature of some 10^9K, again to be compared with the ~ $2x10^7$K which was then thought to be the allowed stellar temperature. It was not realized at that time that it is possible to form ^{8}Be from ^{4}He at a sufficiently high ^{4}He density and temperature and so bypass the mass-4 barrier. So it was that recognition of the crucial role of ^{8}Be in the build-up of the elements had to await the acceptance, in the early 1950's, of a new understanding of the physics of stellar interiors.

In the intervening decade, therefore, attention was diverted toward processes which could have occurred before the formation of the stars, namely a hot dense state associated with the birth of the universe. The formalism associated with the birth of the universe had been laid out by Friedman (1922), Lemaitre (1927) and Einstein and deSitter (1932). The applicability of this formalism to the real world was established by the beautiful simplicity of Hubble's (1929) powerful result that the observed velocities of the "extragalactic nebulae" [i.e. the galaxies which make up the universe] were proportional to their distances from the observer. In its simplest form, the most distant galaxy is moving away at the fastest rate and the nearest at the slowest. This is exactly what one would expect if all the galaxies had begun their flight from a common origin and, at a common starting time, had been given their start in a tremendous explosion.

Not widely popular among respectable scientists of the time, this idea of an expanding universe was taken up in the 1940's in part because the theories of the stellar origin of the elements had failed in the 1930's. (The expanding universe picture was generally ignored again in the 1950's when the wide variety of stellar phenomena became understood. It was only in the 1960's that a more balanced view emerged, but that comes later in our story.) The title of Chandrasekhar and Henrich's 1942 paper "An Attempt to Interpret the Relative Abundances of the Elements and Their Isotopes" reflects the tentative and unsatisfactory nature of the state of understanding at that time. The paper begins, "It is now generally agreed that the chemical elements cannot be synthesized under conditions *now believed* (emphasis added) to exist in stellar interiors." As an alternative, the authors suggested that the expansion and cooling of the early universe might be a possible site for the processes. In this view, each of the elements had its abundance "frozen out" at an appropriate stage of the expansion of the hot ($\geqslant 10^9$K), dense ($\geqslant 10^6$gr/cm^3) universe.

As was shown by George Gamow (1946), however, the formation of elements in the early universe could not have occurred through these equilibrium processes. He accomplished this demonstration by a straightforward calculation of the time scales involved. (The interested general reader can find more on this and related points in the mathematical appendices of S. Weinberg's (1977) delightful book "The First Three Minutes".)

Consider a point mass m located on the surface of an expanding sphere with mass density ϱ. The energy E of the mass with respect to the center of the sphere is a fixed quantity, the sum of its kinetic and potential energies (the latter is a negative quantity), viz

$$E = const = \frac{mv^2}{2} - \frac{Gm(4\pi\rho R^3/3)}{R} \tag{5}$$

where G is the constant of gravitation, ϱ, the density, R, the radius of the sphere, and v, the outward velocity of the point mass, are all functions of time. Since $4\pi\varrho R^3/3$, the mass within the sphere, is not an increasing function of R, the far right-hand term must become arbitrarily large for sufficiently small values of R(t), i.e., at early times in the expansion. Under this "early time approximation" both right-hand terms must become very large because the difference between them is fixed. Thus we can regard the two terms as essentially equal at early times and, upon simple rearrangement, obtain

$$\frac{R(t)^2}{v(t)^2} \approx \frac{3}{8\pi\rho(t)G} \tag{6}$$

Now R/v is a characteristic time scale for the expansion: it is the reciprocal of Hubble's constant and is referred to as the Hubble age in cosmology. (Hubble's "constant" is constant in the spatial sense; it varies in time.) Putting numerical values in (6), we have

$$Age \approx \sqrt{\frac{10^6}{\rho}}\ sec. \tag{7}$$

where ϱ is expressed in gr/cm^3. Thus, as Gamow pointed out, a neutron density of 10^{30}cm^{-3} (about 10^6gr/cm3) would exist for less than one second in the early universe. Since the β-decays necessary to establish the appropriate equalities between protons and neutrons are typically measured in minutes, it is clear that the time period needed to establish equilibrium with neutrons at the high densities required simply was not available in the early expanding universe.

This demonstration set the stage for the consideration of nonequilibrium processes. Fortunately, two timely developments for the undertaking of such a study had just occurred. The first was the publication of the values of neutron capture cross-sections in the open literature after the end of World War II. The second was a bright graduate student in need of a thesis topic. Lifshitz (1946) solved the problem that Gamow's student,

R. A. Alpher, had originally selected for a thesis topic, one having to do with turbulence and galaxy formation in the early universe. As a result, Alpher soon set to work on a new topic, the nonequilibrium formation of the elements by neutron capture. Since not all cross-sections were available, Alpher fitted a smooth curve through the published points, and used this curve for his calculations. The results of Alpher's calculation were introduced to the scientific world in a brief letter whose list of authors makes it part of the folklore of physics (Alpher, Bethe and Gamow 1948).

At this point the trail divides. Two different paths of investigation must be followed before they merge again into final results. We proceed to follow one of them with the understanding that we must return here later to follow the other.

In presenting his thesis results Alpher initiated a series of interactions between scientists which led to a succession of results very different from what he might have expected. First, Enrico Fermi, present at a seminar given by Alpher, soon raised an important objection: The straight line interpolation of capture cross-sections leads to a serious error in the case of the light nuclei. The neutron capture cross-section of a mass-4 particle is known to be essentially zero, whereas Alpher's curve was fitted to the average cross-sections of the nearby nuclei, which are quite large. Fermi had his student Turkevitch redo Alpher's calculations using explicit measured values for the cross-sections. Fermi and Turkevitch's results, never published separately but merely sent directly to Alpher, showed what Gamow and his co-workers knew and admitted privately, that their mechanism could produce nothing heavier than mass-4 from neutrons alone.

Second, Fermi pressed his friend Martin Schwartzschild for observational evidence of the formation of the heavy elements in stars. Together with his wife Barbara, Schwartzschild amply fulfilled this request. In one of the classic papers of observational astronomy (Schwartzschild and Schwartzschild 1950) they measured the faint spectra of two groups of stars of the same stellar type, F dwarfs, stars with long uneventful lifetimes. A separation into two groups, Population I and Population II, was done on the basis of velocity. This distinction, due to Baade, makes use of the fact that interstellar gas is almost totally confined to the galactic plane because vertical (i.e., perpendicular to the plane) gas motions are quickly damped out by cloud-to-cloud collisions. Thus, new stars born from this gas are to be found in the plane, without appreciable vertical motion. (These stars, which are easier to find, were found first and hence are called Population I.) Old stars, formed before the formation of the galactic disc retain the high velocities of the gas from which they were formed because dissipative encounters between stars are negligibly rare. Consequently, older (Pop II) stars can be distinguished by their higher velocities. The Schwartzschilds' comparison of the spectra of the two populations provided a clear answer: the younger Population I stars had the greater abundance of iron and other metals, thus revealing the enrichment of the interstellar medium between the times that the older and younger stars were formed.

This unmistakable evidence of metal production by stars during the lifetime of the galaxy removed the need for a pre-stellar mechanism for element formation. Only the path around the mass-4 barrier for element build-up in stars still had to be found. This was the third and final step.

Martin Schwartzschild presented this challenge to a young nuclear physicist, Ed Salpeter. Salpeter set to work, having a much wider range of accepted stellar conditions to work with than did Bethe in his earlier investigation. He soon found (Salpeter 1952) that ^{8}Be, unstable though it is, can be present in the hot dense cores of red giant stars in sufficient quantities to provide a convenient stepping stone for the formation of ^{12}C through the addition of a helium-4 nucleus.

With both observational support and the theoretical path around the mass-4 barrier, the triumph of stellar element formation now seemed complete. Fred Hoyle dismissed all pre-stellar theories of element build-up as "requiring a state of the universe for which we have no evidence" (Burbidge, et. al. 1957). So much for Alpher and Gamow's theory! "If the curve is simple the explanation must be simple" Gamow (1950) had said. But the curve of elemental abundances is not a simple one (Fig. 2). Burbidge et. al. presented no less than seven separate processes to account for the data, and left room for more under an eighth heading to fill in the few remaining gaps of their picture.

Ironically, it was Fred Hoyle himself who found a gap that could not be filled in the stellar picture, a gap in the best-understood process of them all, the formation of helium from hydrogen. Although the burning of hydrogen into helium provides the sun and the other stars with their energy and with building blocks for the formation of the heavier elements, Hoyle concluded that about ninety percent of the helium found in stars must have been made before the birth of the galaxy. The basis for this conclusion was an energy argument: the total amount of energy released by the formation of all the observed helium is some ten times greater than the energy radiated by the galaxies since their formation. Thus, "it is difficult to suppose that all the helium has been produced in ordinary stars" (Hoyle and Taylor 1964). Instead, attention was turned to helium formation in the early stages of an expanding universe, reviving work begun by George Gamow some sixteen years earlier. As indicated above, our description of Gamow's work was deferred in order to first follow the progress of the stellar picture of element build-up. We can now follow the second path.

Despite the problems inherent in Alphers treatment, (see, e.g., Alpher and Herman 1950), it provided the basis for a statement of profound simplicity and great power (Gamow 1948). Although wrong in almost every detail, Gamow's new insight pointed the way for others to follow. He noted that nuclear build-up cannot take place in the hottest, most condensed, state of the early universe because thermal photons at high temperatures $\geqslant 10^{10}$K are energetic enough to break up bound particle groups. Only when the temperature has cooled to $\sim 10^{9}$K, can nuclear reactions begin. Any build-up, however, must be completed during the few hundred seconds before all the free neutrons decay into protons. Gamow considered a cylinder (Fig. 3) swept out by a neutron with a 10^9K thermal velocity during its lifetime. The cross-section of the cylinder was the capture cross-section for deuteron formation. If there was to have been appreciable element build-up in the early universe, Gamow reasoned, some fraction, say one half, of the initial neutrons had to have collided with protons to form deuterons before they had time to decay. Thus, half of Gamow's sample cylinders should contain a proton. This statement determines the number of protons per unit volume. From this result, the mass of the proton, and his estimate of the fraction of matter that was in the form of protons (roughly one half), Gamow obtained the mass density of matter in the universe at 10^9K, about 10^{-6}gm/cm^3.

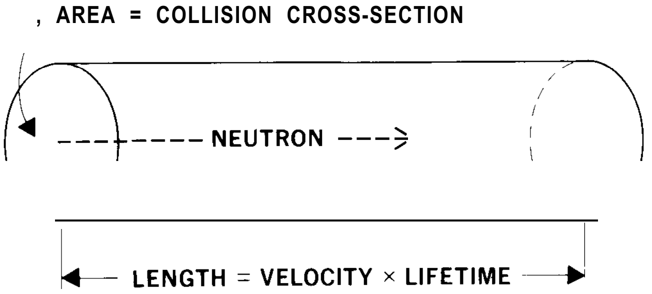


Fig. 3 *Gamows Sample Cylinder;* The volume swept out by a neutron in the early universe. The length of the cylinder is the product of the neutron's thermal velocity (at 10^9K) and its decay time. The cross-sectional area is the neutron-proton collision cross-section for deuteron formation. The fraction of neutrons forming deuterons is equal to the probability that the cylinder contains a proton.

Gamow then noted that the mass density of radiation at 10^9K (i.e., its energy density divided by c^2) was about 10gr/cm^3, as compared with only 10^{-6}gr/cm^3 for matter. This makes radiation the dominant component in the entropy of the early universe, permitting it to cool during the expansion as if the matter were not present. In that case, the temperature varies inversely with the radius of the expanding volume element (Tolman 1934, Peebles 1971) i.e.,

$$T \propto R^{-1}. \qquad (8)$$

Now since ρ, the density of matter, varies inversely as the cube of the radius, we can replace (8) with

$$T \propto \sqrt[3]{\rho}. \qquad (9)$$

or

$$\frac{T_1}{T_2} = \sqrt[3]{\frac{\rho_1}{\rho_2}}\,.$$

This neat relation between temperature and matter density holds as long as radiation remains the dominant component. When the temperature drops below ~ $3x10^3$K, the matter is too cool to remain ionized, and once it becomes neutral it is essentially transparent to the radiation. The radiation is then no longer coupled to the matter, it is free to expand forever in untroubled isolation, and eqn (9) continues to apply.

Gamow was only interested in tracing the radiation to the epoch when the matter becomes neutral and decouples from the radiation. From that point on, the matter has only its own thermal energy to support itself against gravitational collapse, so it fragments and condenses to form galaxies. Gamow used eqn (9) to find the density of matter at 3X 10^3K and the Jeans criterion to determine the size of the collapsing fragments. Thus he was able to obtain a relation for the mass of galaxies containing only fundamental constants and the single assumption that half the initial neutrons collided to form deuterons. This was quite a trick, even for him!

Gamow's paper inspired his former student, Alpher and his collaborator Robert Herman to do the calculations more rigorously (Alpher and Herman 1949). Most importantly they replaced the "early-time" approximation Gamow used with a more exact formulation and traced the temperature of the relict primordial radiation to the present epoch. Taking the present matter density of the universe to be 10^{-30}gm/cm^3, they concluded that the present energy density of the relict radiation should correspond to a temperature of a few degrees Kelvin. Although mention of this prediction persisted in Gamow's popular writing, it was only repeated explicitly in a few of their subsequent scientific works. As for detection, they appear to have considered the radiation to manifest itself primarily as an increased energy density (Alpher and Herman 1949, pg. 1093). This contribution to the total energy flux incident upon the earth would be masked by cosmic rays and integrated starlight, both of which have comparable energy densities. The view that the effects of three components of approximately equal additive energies could not be separated may be found in a letter by Gamow written in 1948 to Alpher (unpublished, and kindly provided to me by R. A. Alpher from his files). "The space temperature of about 5° K is explained by the present radiation of stars (C-cycles). The only thing we can tell is that the residual temperature from the original heat of the Universe is *not higher* than 5° K." They do not seem to have recognized that the unique spectral characteristics of the relict radiation would set it apart from the other effects.

The first published recognition of the relict radiation as a detectable microwave phenomenon appeared in a brief paper entitled "Mean Density of Radiation in the Metagalaxy and Certain Problems in Relativistic Cosmology", by A. G. Doroshkevich and I. D. Novikov (1964a) in the spring of 1964. Although the English translation (1964b) appeared later the same year in the widely circulated "Soviet Physics-Doklady", it appears to have escaped the notice of the other workers in this field. This remarkable paper not only points out the spectrum of the relict radiation as a blackbody microwave phenomenon, but also explicity focuses upon the Bell Laboratories twenty-foot horn reflector at Crawford Hill as the best available instrument for its detection! Having found the appropriate reference (Ohm 1961), they misread its results and concluded that the radiation predicted by the "Gamow Theory" was contradicted by the reported measurement.

Ohm's paper is an engineering report on a low-noise microwave receiving system. The reported noise of this system contained a residul excess of almost exactly three degrees! Ohm had measured a total system noise temperature of some 22K including the contribution of the receiver, the antenna, the atmosphere and the sky beyond. Separate measurements of each of the components of this noise temperature, except the sky beyond the atmosphere, totalled - 19K. (From an analysis of his measurement errors, Ohm concluded that both sets of measurements, the total and the sum of individual contributions, could be consistent with an intermediate value). The atmospheric contribution was measured by moving the antenna in elevation and fitting the change in system temperature to a cosecant relation, a standard procedure which is described by Wilson (1978). To avoid confusion with other quantities, the atmospheric contribution thus derived was denoted T_{sky}, the "sky temperature". Ohm's value of 2.3K for this quantity was in good agreement with atmospheric attenuation theory. The background contribution due to the relict radiation has no elevation dependence and cannot be detected by this technique. Perhaps due to the unfortunate name, Doroshkevitch and Novikov regarded T_{sky}, as containing the background radiation and therefore leading to a null result. The disappointment is reflected in Section IV of Zeldovitch's concurrent (1965) review.

The year 1964 also marked a reawakened interest in the "Gamow Theory" by Hoyle and Taylor (1964) as well as the first unambiguous detection of the relict radiation. The rough outlines of Gamow's initial treatment had long since been refined by the work of others. For example, it was pointed out by Hayashi (1950) that the assumption of an initial neutron material was incorrect. The radiation field at $T > 10^9$K generates electron- positron pairs which serve to maintain quasi-thermal equilibrium between neutrons and protons (see also Chandrasekhar and Henrich, 1942, who made the same point). Alpher, Follin and Herman (1953) incorporated this process into their rigorous treatment of the problem. Their work benefited from the availability of what was, by the standard of those days, a powerful electronic computer which permitted them to include the dynamic effects of expansion and cooling upon collisional and photo-disintegrated processes. Their results, which have not been substantially altered by subsequent work, are chiefly marked by (1) conversion of some 15 %′ of the matter into helium, with the exact amount dependent only slightly upon the density at $T \approx 10^9$K and (2) production of deuterium whose surviving abundance is sensitively dependent upon the initial temperature/density relation. The same ground was covered in Hoyle and

Taylor's 1964 paper, which cited Alpher, Follin and Herman's paper and noted the agreement with the earlier results. Neither paper made any mention of surviving relict radiation.

Shortly thereafter, P. J. E. Peebles treated the same subject for a different reason. R.H. Dicke had, with P.G. Roll and D.T. Wilkenson, set out to measure the background brightness of the sky at microwave wavelengths. At his suggestion, Peebles began an investigation of the cosmological constraints that might be imposed by the results of such a measurement. Peebles' paper, which was submitted to the Physical Review and circulated in preprint form in March of 1965. This paper paralleled the above light element production picture and included Hoyle and Taylor (1964) among its references. In addition, it explicitly delineated the surviving relict radiation as a detectable microwave phenomenon. At about the same time, microwave background radiation was detected at Bell Laboratories and its extragalactic origin established. No combination of the then known sources of radio emission could account for it. Receipt of a copy of Peebles' preprint solved the problem raised be this unexplained phenomenon. Eddington tells us: "Never fully trust an observational result until you have at least one theory to explain it. "The theory and observation were then brought together in a pair of papers (Dicke et al, 1965, Penzias and Wilson 1965) which led to decisive support for evolutionary cosmology and further renewal of interest in its observational consequences.

The existence of the relict radiation established the validity of the expanding universe picture with its cosmological production of the light elements, deuterium, helium-3 and helium-4 during the hot early stages of the expansion. The build-up of the heavier elements occurs at a much later stage, after the stars have formed. In stars, the cosmologically produced helium-4, together with additional amounts of helium produced by the stars themselves, is converted (via beryllium-8) into carbon-12 from which the heavier elements are then built. The stellar process described by Burbidge et al (1957) have been supplemented and, in some cases, replaced by processes whose existence was established trough later work, of which explosive nucleosynthesis is the most significant one. (See Clayton 1968 for a review.) Much of the build-up of the heavier elements goes on in a few violent minutes during the life of massive stars in which their outer shells are thrown outward in supernova explosions. This mechanism accounts both for the formation of the heavy elements as well as for their introduction into interstellar space. Thus, the total picture seems close to complete but puzzling gaps remain, such as the absence of solar neutrinos (Bahcall and Davis, 1976). One thing is clear however, observational cosmology is now a respectable and flourishing science.

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REFERENCES

1. Alpher, R. A., Bethe, H. A., and Gamow, G., 1949, Phys. Rev. 73. 803.
2. Alpher, R. A. and Herman, R. C., 1949, Phys. Rev. 75, 1089
3. Alpher, R. A. and Herman, R. C., 1950, Rev. Mod. Phys.22. 153.
4. Alpher. R. A., Follin, J. W. and Herman, R. C., 1953, Phys. Rev. 92, 1347.
5. Bethe, H. A., 1939, Phys. Rev. 55, 434.
6. Burbidge, E. M., Burbidge, G. R., Fowler, W. A., and Hoyle, F., 1957, Rev. Mod. Phys. 29, 547.
7. Chandrasekhar, S., 1939, ***An Introduction to the Study*** of ***Stellar Structure,*** (University of Chicago).
8. Chandrasekhar, S. and Henrich, L. R., 1942, Ap. J. 95, 228.
9. Clayton, D. D., 1968 ***Principles of Stellar Evolution and Nucleosynthesis*** (McGraw-Hill).
10. Dicke, R. H., Peebles, P. J. E., Roll, P. G. and Wilkinson, D. T., 1965, Ap. J. 142, 414.
11. Doroshkevich. A. G. and Novikov, I. D.. 1964a Dokl. Akad. Navk. SSR 154, 809.
12. Doroshkevich, A. G. and Novikov, I. D., l964b Sov. Phys-Dokl. 9. 111.
13. Einstein, A. and deSitter, W., 1932 Proc. Nat. Acad. Sci. ***18***, 312.
14. Eddington, A. ***S.***, 1926, ***The Internal Constitution of the Stars***, (Cambridge University Press).
15. Fowler, R. H., 1926, M.N.R.A. 87, 114.
16. Friedmann, A., 1922. Zeits. Fur Physik 10, 377.
17. Gamow, G., 1946, Phys. Rev. 70, 572.
18. Gamow, G., 1948, Nature ***162, 680.***
19. Gamow, G., 1950, Physics Today 3, No. 8, 16
20. Hayashi, C., 1950, Prog. Theo. Phys. (Japan) 5, 224.
21. Hoyle, F. and Taylor, R. J., 1964, Nature 203, 1108.
22. Hubble, E. P., 1929, Proc. N.A.S. 15, 168.
23. Lemaitre, G., 1927, Ann. Soc. Sci. Brux. ***A47, 49.***
24. Lifschitz, E., 1946, J. Phys. USSR ***10, 116.***
25. Ohm. E. A., 1961, Bell Syst. Tech. J. 40, 1065.
26. Peebles, P. J. E., 1971, Physical Cosmology (Princeton University Press).
27. Penrias, A. A. and Wilson, R. W., 1965, Ap. J. 142, 419.
28. Salpeter, E. E., 1952. Ap. J. ***115, 326.***
29. Schwartzchild, B. and Schwartzschild, M. 1950, Ap. J. 212, 248.
30. Tolman, R. C., 1934, Relativity ***Thermodynamics and Cosmology,*** (Clarendon Press, Oxford).
31. von Weizsäcker, C. F., 1937, Physik. Zeits. 38, 176.
32. von Weizsäcker, C. F., 1938, Physik. Zeits. 39, 633.
33. Weinberg, S., The First Three Minutes, (Basic Books).
34. Wilson, R. W., 1978 Nobel Lecture
35. Zeldovich, 1965, Advances in Astr. and Ap.3. 241.