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Gamow's cosmology

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This essay, written on the occasion of the 111$^{\text{th}}$ anniversary of George Gamow's birth in Odessa, reviews developments in cosmology in the late 1940s by Gamow and colleagues. Gamow's deep physical insight and imagination, along with his inclination to leave the details to others, is well illustrated by the paper by Alpher, Bethe and Gamow (Alpher, R.A., Bethe, H., & Gamow, G. 1948, Physical Review, 73, 803), which is celebrated but wrong, and Gamow's paper that soon followed (Gamow, G. 1948a, Physical Review, 74, 505), which corrected the problem by introducing basic elements of the established theory of cosmic evolution from a hot dense early state of expansion of the universe.

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1 Introduction

The research by George Gamow, Ralph Alpher, and Robert Herman foreshadowed to a remarkable degree the theory of cosmic evolution that a half century later became well tested and established. In 1948 Gamow, Alpher, and Herman published often. An unfortunate consequence is that references to their work tend to cite only one or two of their papers, often missing the one that got it right. A fortunate consequence is that we can follow the development of their thinking in some detail. This review of the situation draws from and enlarges on the discussion in Peebles (2014).

2 Earlier ideas about nucleosynthesis

Gamow's cosmology was foreshadowed in part by analyses of the idea that the relative abundances of the chemical elements may have been determined by relaxation to Saha statistical equilibrium at temperatures in the range of 10^9 to 10^{10} K (e.g. von Weizsäcker 1938; Chandrasekhar and Henrich 1942; Klein, Beskow and Treffenberg 1946). It was supposed that this relaxation might have happened in extreme conditions in stars, or else that, as Chandrasekhar and Henrich put it, "the cause of the

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original expanding and cooling ... may be connected with the beginning of the expansion of the universe." These early discussions did not note that their application of the Saha relation for the relative abundances of atomic nuclei implicitly assumed statistical equilibrium with a sea of thermal radiation. And there was no consideration of the relative rates of expansion and nuclear reactions. Gamow (1942) seems to have been the first to point out that in an expanding universe one may have to consider non-equilibrium element formation processes. Gamow (1946) was more explicit, writing that, in the relativistic Friedman–Lemaître model, the large mass density in the early stages of expansion of the universe requires rapid expansion, making it "very dangerous to speak about an equilibrium state." Gamow (1946) suggested instead that in the very early universe free neutrons "were gradually coagulating into larger and larger neutral complexes which later turned into various atomic species by subsequent processes of β-emission."

Gamow (1935) had earlier discussed the general idea of element buildup by radiative capture of neutrons, though applied to reactions in stars. We see evolution of his thinking in the book on nuclear physics by Gamow and Critchfield (1949). (The book was published in 1949, but as will be discussed the text of interest was written no later than early 1948). Chapter X §6 in the book recalls the proposal that the elements grew "as *aggregations of neutrons*", and presents an expression for the buildup of the elements by successive neutron captures,

$$\frac{dN_i}{dt} = N_0 v(\sigma_{i-1}N_{i-1} - \sigma_i N_i), \quad (i = 1, 2, 3, \ldots). \tag{1}$$

Here N_i is the number density of species with atomic weight i and $\sigma_i v$ is the rate constant for radiative neutron capture by atomic nuclei with atomic weight i. Beta decays were presumed to keep the neutron-to-proton ratio close to the valley of stability. A footnote in the book states that "More detailed calculations on this non-equilibrium process are being carried out by R.A. Alpher and will be published in due course."

The numerical solution of equation (1) was the subject of Alpher's (1948a) doctoral dissertation. Since the illustration of the nature of the solution in Gamow and Critchfield (1949) is much more crude than was presented in Alpher's thesis, I take it that the footnote mentioning Alpher was written when he was not very far along in his thesis research. The evidence is that Alpher deserves credit for finding measurements of neutron radiative capture rates $\sigma_i v$ for "MeV reactor neutrons." He used a smooth fit of $\sigma_i v$ as a function of i in his computation of numerical solutions to equation (1). That was not an easy task in those days. Alpher's parameter to be adjusted for the best fit to the measured relative abundances was the time integral of the neutron number density $n(t)$. Alpher (1948a) found that the integrated exposure

$$\langle nt \rangle = \int_{t_0}^{\infty} n(t)\, dt = 0.81 \times 10^{18} \text{ s cm}^{-3} \tag{2}$$

produces a reasonable fit to the trend of measured abundances with atomic weight i, under the important assumption that the smooth approximation to $\sigma_i v$ as a function of i is warranted.

As Alpher was completing his dissertation his results were published by Alpher, Bethe and Gamow (1948). As is widely celebrated, Gamow added Hans Bethe to the author list to produce an approximation to α, β, γ. And the paper is rightly celebrated

as a step toward our now established cosmology. But the paper is wrong. The paper states that "In order to fit the calculated curve with the observed abundances it is necessary to assume that the integral of $\rho_n dt$ during the building-up period is"

$$\int_{t_0}^{\infty} \rho_n \, dt = 5 \times 10^4 \text{g s cm}^{-3}. \tag{3}$$

The corresponding value of the integral of the baryon number density is

$$\langle nt \rangle = \int_{t_0}^{\infty} n(t) \, dt \sim 3 \times 10^{28} \text{ s cm}^{-3}. \tag{4}$$

This is some ten orders of magnitude larger than Alpher's fit in equation (2).

We have a check that the value of $\langle nt \rangle$ from equation (3) is not a misprint. In a Friedman–Lemaître model dominated by non-relativistic baryons the time integral of the mass density agrees with equation (3) if $t_0 = 20\,\text{sec}$, the value stated in Alpher, Bethe and Gamow (1948).

At the exceedingly large value of $\langle nt \rangle$ in equation (4) protons as they were produced by neutron decay would be promptly captured by neutrons to produce deuterons, and from them heavier elements, leaving little hydrogen. This is quite contrary to what was known then about the composition of stars (as reviewed in Haramundanis 1996 and Trimble 2010, p. 92). One could choose the starting time t_0 for nucleosynthesis to be just such that a substantial but not total fraction of the neutrons had decayed before nucleosynthesis commenced, so we would be left with a significant mass fraction in hydrogen, but this awkward arrangement rightly has received no attention.

3 Gamow's cosmology

Ganow introduced the Hot Big Bang Cosmology to resolve the vast discrepancy between equations (2) and (4). Alpher (1948a) had already pointed out the discrepancy in his thesis. Gamow (1949) later took note of the discrepancy, in a paper in *Reviews of Modern Physics*, and explained his resolution. But apart from that and comments in later papers by Alpher and Herman I have not been able to find notice taken of the problem with Alpher, Bethe and Gamow (1948) in the many citations of the paper prior to the book *Finding the Big Bang* (Peebles, Page and Partridge 2009). I share the fault in not noticing this earlier, and can only lament our often indifferent attention to our own history.

The Alpher, Bethe and Gamow (1948) paper is marked as received by *The Physical Review* on 18 May. On 21 June the journal received the paper Gamow (1948a) that resolved problem and explained what determined the starting time t_0 for nucleosynthesis. I take it as characteristic of Gamow's style that he only notes that the integral of $\rho_n dt$ "was given incorrectly in the previous paper." Gamow's new proposal was that

> "Since the building-up process must have started with the formation of deuterons from the primordial neutrons and the protons into which some of these neutrons have decayed, we conclude that the temperature at that time must have been of the order $T_0 \simeq 10^9$ °K (which corresponds to the dissociation energy of deuterium nuclei)".

This statement requires analysis, again something I take to be characteristic of Gamow's writing. What did he mean by "dissociation energy of deuterium nuclei"?

The binding energy of the deuteron is an order of magnitude larger than kT_0 at Gamow's $T_0 \simeq 10^9$ K, where k is Boltzmann's constant. Gamow certainly knew that. The deuteron binding energy is stated and used in discussions of the nuclear force in Gamow (1937) and Gamow & Critchfield (1949). Thus I take it that by "dissociation energy" he did not mean the deuteron binding energy. Gamow was familiar with the Saha relation: It was used in the computations by Chandrasekhar and Henrich (1942) that were reviewed in Gamow and Critchfield (1949). It will be recalled that in the established cosmology application of the Saha equilibrium relation to the reactions

$$\mathrm{n} + \mathrm{p} \leftrightarrow \mathrm{d} + \gamma \tag{5}$$

tells us that, since the dimensionless entropy per baryon is large in the early universe, nucleosynthesis was suppressed until the temperature fell to a critical value close to Gamow's T_0. At that point the balance in equation (5) abruptly shifted from photodissociation of deuterium at $T \gtrsim T_0$ to suppression of photodissociation and accumulation of deuterium at $T \lesssim T_0$. Deuterium then soon became abundant enough to burn to heavier elements by relatively fast particle exchange reactions. Thus it seems clear that Gamow (1948a) had in mind this modern picture for how nucleosynthesis commenced, though I wish he had been more specific.

Alpher (1948a), in his thesis, presented the first published argument that in the picture of element buildup by radiative capture of neutrons the universe might be expected to have been filled with a sea of thermal radiation. The argument presented in his thesis was that element buildup likely occurred at neutron kinetic temperature $T_0 \sim 10^9$ K, because this avoids collisional dissociation at higher kinetic energy and it avoids resonances at lower energy that would spoil the general inverse relation between element abundance and neutron capture cross section. Alpher pointed out that neutrons at kinetic temperature $T_0 \sim 10^9$ K might naturally be expected to have been accompanied by thermal radiation at the same temperature. And he noted that, if so, one would have to take account of the mass density in radiation, meaning "An interpretation of the starting time and initial density for the neutron-capture process will therefore require the development of a new cosmological model."

An earlier precedent for the idea that the universe might be filled with a sea of thermal radiation was the study of the Saha equilibrium relation for element abundances. Although none of the early studies stated it, the Saha relation assumes statistical equilibrium with a sea of thermal radiation. Still earlier, Tolman (1934, p. 427) had shown that a free sea of thermal radiation in a homogeneous and isotropic expanding universe would cool as the universe expanded but preserve the thermal spectrum characteristic of the observed Cosmic Microwave Background radiation (the CMB). But the central point for the theory of Hot Big Bang nucleosynthesis is that the radiation sets the time t_0 for the onset of the build-up of the elements in an expanding Friedman–Lemaître cosmological model through the abrupt change of balance of equation (5) as the universe expanded and cooled through $T_0 \sim 10^9$ K. To my knowledge this point appears for the first time in Gamow (1948a).

In the early stages of expansion of the universe the mass density in radiation would have been much larger than the mass density in matter, meaning the rate of expansion of the early universe would have been determined by the radiation temperature. At

$T_0 = 10^9$ K the expansion time in the Friedman–Lemaître model is $t_0 = 230$ sec. Gamow's (1948a) condition for significant but not excessive production of elements heavier than hydrogen is

$$\sigma v n_0 t_0 \sim 1, \tag{6}$$

where the nucleon number density at radiation temperature T_0 is n_0, and v is the typical relative velocity of what are supposed to be comparable numbers of neutrons and protons. Gamow (1948a) got the capture cross section $\sigma \simeq 10^{-29}\,\mathrm{cm}^2$ from Hans Bethe, v from the thermal velocity of nucleons at $T_0 \sim 10^9$ K, t_0 from the expansion time, and concluded from equation (6) that the baryon density was

$$n_0 \sim 10^{18}\ \mathrm{cm}^{-3}\ \ \text{at}\ \ T_0 \simeq 10^9\ \mathrm{K}. \tag{7}$$

This is not far from the established modern value of the baryon density n_0 at the start of element buildup.

Having T_0 and n_0, and an estimate of the present baryon mass density $\rho_{\rm present} = mn_{\rm present}$, where m is the baryon mass, one can use the relation $T(t) \propto n(t)^{1/3}$ to compute the present radiation temperature, $T_{\rm CMB}$, of what we now identify as the CMB. In their papers Alpher, Gamow and Herman consistently used the present baryon density

$$\rho_{\rm present} = 10^{-30}\ \mathrm{g\ cm}^{-3}. \tag{8}$$

Gamow (1948a,b) certainly recognized that the sea of radiation would be present after element buildup, and would have affected cosmic evolution (as discussed in Section 5 below), but he does not seem to have taken much interest in the present radiation temperature. Alpher and Herman (1948a) took this critical step. They concluded that "the temperature in the universe at the present time is found to be about 5° K." This is strikingly close to the measurement many years later, 2.726 K. But this rightly celebrated statement calls for consideration of two points.

First, the predicted value of $T_{\rm CMB}$ depends on the present baryon mass density. I know of two citations that suggest the source of the baryon density in equation (8). Gamow (1946) stated this density and, later in the paper, in connection with Hubble's constant, referred to Hubble (1936). Hubble (1936) used counts of nebulae, or galaxies, and estimates of galaxy masses derived from internal velocities, to conclude that the mean mass density is no less than $10^{-30}\,\mathrm{g\,cm}^{-3}$, the value in equation (8). But Hubble found that the density could be as large as $10^{-28}\,\mathrm{g\,cm}^{-3}$ if he used the mean mass per galaxy derived from the Virgo Cluster. Alpher and Herman (1949) attributed the mass density in equation (8) to Hubble (1937), where it is reported that "the smoothed-out density of nebular material" is "between 10^{-29} and 10^{-30} grammes per cubic centimeter," a lower limit "because it ignores the matter that may lie between the nebulae." That is, Hubble was far less definite about the mass density than one might infer from the consistent use of equation (8) by Alpher, Gamow and Herman. It is to be borne in mind also that Hubble's extragalactic distance scale was off by an order of magnitude. On the other hand, the considerable uncertainty in $\rho_{\rm present}$ translates to less uncertainty in $T_{\rm CMB}$ because the CMB temperature scales as the cube root of the density.

Second, Alpher and Herman differed from Gamow on how best to estimate n_0. Gamow chose n_0 to permit significant but not excessive production of deuterium at

the onset of nucleosynthesis, leaving for future work the details of how particle exchange reactions and further radiative captures would redistribute the baryonic mass to heavier elements. This allowed a useful approximation to the mass fraction remaining as hydrogen. Alpher and Herman (1949) wrote that "We believe that a determination of the matter density on the basis of only the first few light elements is likely to be in error". They chose to adjust n_0 at T_0 to fit the broad run of relative element abundances with atomic weight i, in numerical solutions of the buildup equation (1), using the smoothed trend of $\sigma_i v$ with i. But Alpher (1948b) foresaw the failure of their approach: Element buildup beyond helium is suppressed by the absence of an acceptably long-lived nucleus of atomic weight 5. The suppression was confirmed by Enrico Fermi and Anthony Turkevich, as reported by Gamow (1949) and in more detail by Alpher and Herman (1950).

Table 1 Estimates of the CMB temperature.

ρ_0, g cm^{-3}	$T_{\rm CMB}$, K	Reference
2.0×10^{-6}	8	Gamow 1948a
1.4×10^{-7}	19	Alpher and Herman 1948a
5×10^{-9}	60	Alpher and Herman 1948b
4.8×10^{-6}	5.9	Alpher and Herman 1949

Although Gamow's approach proves to be the correct one it is interesting to compare the present radiation temperature $T_{\rm CMB}$ indicated by the several early estimates of the nucleon number density n_0 at the start of nucleosynthesis. The values of n_0 in Table 1 are drawn from the cited publications. The present temperatures, $T_{\rm CMB}$, are my computations from the n_0 and the present density in equation (8). The temperature indicated by Gamow's (1948a) original estimate of n_0 (equation (7)) in the first line is not unreasonably larger than the measured value, considering all the uncertainties. I do not know any evidence that Gamow actually computed this temperature, however. Alpher and Herman (1948a) presented a considerable list of corrections to Gamow's (1948a) computation, and reported that "Correcting for these errors, we find" $\rho_{\rm mat.} = 4.83 \times 10^{-4}/t^{3/2}$. With $t = 231$ s at T_0 in a radiation-dominated universe this translates to the baryon density in the second line of Table 1. It indicates a still larger present temperature, well above the "about 5° K" stated in the paper. The likely interpretation is that Alpher and Herman (1948a) did not use n_0 derived by Gamow's approach, but rather used the fit to the broad run of element abundances reported in Alpher and Herman (1949), where we read that their result "corresponds to a temperature now of the order of 5° K." This agrees with the "about 5° K" reported in Alpher and Herman (1948a), and it agrees reasonably well with my computation entered in the last line of the table. The value of ρ_0 in the third line, from Alpher and Herman (1948b), is stated also in the Alpher, Herman, and Gamow (1949) abstract for a contributed paper to the November 26–27 1948 meeting of the American Physical Society. Since the abstract almost certainly was submitted before the conference started, and the paper Alpher and Herman (1948b) was submitted to the publisher on 1 September, it seems likely that the authors reported the result of the same computation in paper and abstract. It indicates a considerably higher present temperature, ∼60 K. But it seems that Alpher and Herman (1949) returned

to a larger ρ_0, with $T_{\rm CMB}$ consistent with their first report in 1948.

In short, Alpher and Herman are to be honored for a signal advance in presenting the first estimate of the CMB temperature. But the similarity of their stated value with the measured temperature is not to be taken seriously.

4 Gamow and the origin of helium

Another complicated and historically interesting story is the steps toward the evidence that helium largely originated in the early universe. Gamow (1948b) presented a numerical computation of the buildup of deuterium in his picture, ignoring the conversion of deuterons to heavier elements. His choice of parameters indicated remnant hydrogen mass fraction $X \sim 0.6$, which is in line with his statement in the paper that "hydrogen is known to form about 50 percent of all matter." The idea was repeated in Gamow (1953), where he showed a computation of element buildup by Fermi and Turkevich, with final hydrogen mass fraction $X \sim 0.6$ and helium mass fraction $Y \simeq 0.36$, "in good agreement with the observed relative amount of Hydrogen and Helium in the universe."

Gamow's impression that the helium abundance is large was not supported by much evidence. He might have had in mind the discussion in Gamow and Critchfield (1949) of Schwarzschild's (1946) Solar model, in which the relative masses in hydrogen, helium, and heavier elements are stated, in the paper and the book, as

$$X = 0.47,\ Y = 0.41,\ Z = 0.12. \tag{9}$$

At the time Fred Hoyle had a quite different opinion about Y. In his generally positive review of the book on nuclear physics by Gamow and Critchfield (1949), Hoyle (1950) wrote that

> "a calculation is given purporting to show that the Sun contains 41% helium. This calculation depends critically on the assumption that the chemical composition of the Sun is uniform. As this is unlikely to be valid the conclusion is hardly likely to be of much value."

Consistent with this sentiment, Hoyle (1949) wrote that "hydrogen still constitutes about 99 per cent of all material." This was based on his estimate of the production of helium in stars, which he found to be a small fraction of the mean baryon density, and his unstated assumption of negligible primeval helium. Hoyle (1949) cited the Steady State papers by Hoyle, Bondi and Gold as in press. In this then new Steady State cosmology one is free to postulate continual creation of helium as well as neutrons or protons and electrons, but I have seen no arguments for the idea. And we are free to speculate that the Steady State model with continual creation of free nucleons, with the small production of helium in stars, contributed to Hoyle's sense that the helium abundance likely is small.

Did the weight of evidence in the early 1950s favor Gamow's high helium abundance or Hoyle's low abundance? Hoyle's (1950) objection to Schwarzschild's (1946) Solar model is no longer discussed, but the model may be criticized for its convective core and radiative envelope. However, the Schwarzschild, Howard, and Härm (1957)

Solar models with convective envelope and radiative core, and with $Z \gtrsim 0.015$, which the authors stated is indicated by spectroscopic observations, have initial helium mass fraction $Y \gtrsim 0.2$. Hoyle and Schwarzschild (1955), in their study of the evolution of the old Population II stars, used $Y = 0.1$, but there is no citation of evidence for this compromise between the high and low helium abundance camps. Unsöld (1948) found high helium abundance in τ Scorpii, but one might question whether this massive star is a fair sample. Aller and Menzel (1945, Table 6, in a summary of a series of prewar papers) found that the helium abundance in planetary nebulae is about 10% of hydrogen by number, or helium mass fraction $Y \sim 0.3$. But one might wonder whether this helium was produced in the evolving stars. I conclude that in the early 1950s there were indications of Gamow's high helium abundance, but they certainly were not persuasive.

By the early 1960s the improved evidence for $Y \sim 0.3$ led Osterbrock and Rogerson (1961) to remark that

> "The helium abundance $Y = 0.32$ existing since such an early epoch could be at least in part the original abundance of helium from the time the universe formed, for the build-up of elements to helium can be understood without difficulty on the explosive formation picture.[21]"

The reference (21) is to Gamow (1949). Burbidge (1962) referred to Osterbrock and Rogerson (1961), and noted, as the last of four possible explanations of the evidence for a high helium abundance, that

> "The bulk of the transmutation of H to He took place in the first few minutes in the expansion of the Universe."

Burbidge cited Alpher and Herman (1950) and Gamow (1953). Here are respected scientists pointing to possible evidence for Gamow's cosmology: the high abundance of helium compared to what might be expected to have been produced in stars. But I have found no indication that the community noticed.

Hoyle and Tayler (1964) reviewed the evidence that $Y \sim 0.3$. For the Hot Big Bang theory of why Y is so large they cited Alpher, Bethe and Gamow (1948), which was wrong, but also Hayashi (1950) and Alpher, Follin and Herman (1953), which were on the right track. We cannot know whether the Hoyle and Tayler (1964) paper would have at last attracted interest in Gamow's cosmology, however, because in the following year wide attention was drawn to another piece of evidence, the sea of microwave radiation, and the proposed interpretation as the "Primeval Fireball." It is now known as the CMB. It could have been termed "Gamow's Radiation," but we were slow to recognize the connection.

5 Gamow and the origin of galaxies

The paper "On the Origin of the Great Nebulae" by Gamow and Teller (1939) exemplifies Gamow's long-standing interest in how the galaxies formed. Gamow (1948a,b) used the numbers in equation (7) to estimate the temperature at equality of mass densities in matter and radiation, $T \simeq 10^3\,\mathrm{K}$. And he recognized, perhaps by intuition,

that this marks the start of the gravitational growth of clustering of nonrelativistic matter (provided one can ignore the radiation drag on the plasma before the transition to largely neutral baryonic gas). Gamow and Teller (1939) pointed out that the matter kinetic temperature determines the Jeans length at the minimum scale for gravitational growth of clustering of matter in the expanding universe. Gamow (1948b) had a temperature, and he used it to compute the Jeans mass, $M = 2.7 \times 10^7 M_\odot$. This is three orders of magnitude below the mass in stars in our Milky Way galaxy, but still it is an interesting quantity in galaxy formation theory.

Lifshitz (1946), in his pioneering analysis of the growth of linear departures from the homogeneous Friedman–Lemaître model, concluded (in the abstract) that gravitational instability "cannot serve as centers of formation of separate nebulae or stars." The analysis was correct, but not the conclusion. Lifshitz had shown that in linear perturbation theory departures of spacetime curvature from homogeneity never grow large. This is true of the established ΛCDM cosmology (apart from nonlinear growth of spacetime curvature very near black holes). But small primeval departures from a homogeneous mass distribution can grow large, as in galaxies, while producing small perturbative adjustments to spacetime. Perhaps Gamow had not noticed Lifshitz's conclusion. Perhaps he noticed and recognized that Lifshitz's analysis was incomplete. But in any case Gamow proves to have been taking substantial steps toward the modern picture of galaxy formation.

6 Concluding remarks

I use the term "Gamow's cosmology" because Gamow (1948a,b) saw, by some combination of physical analysis and remarkable intuition, that detailed balance of radiative formation and dissociation of deuterium in thermal radiation in the early universe would have determined the start of nucleosynthesis, beginning with rapid buildup of deuterium, and that the radiation also would have set the start of gravitational growth of cosmic structure, at the time of equality of mass densities in matter and radiation. Alpher (1948a) and Alpher and Herman (1948b, 1949, 1950) computed relative element abundances in the wrong picture. After starting them on their path Gamow (1948a,b) abruptly changed his mind. Alpher and Herman are to be credited for pioneering studies that figure now in r-process element formation in stars, and for their early development of numerical methods for machine computation, no easy task. The Alpher, Follin and Herman (1953) computation of the evolution of the ratio n/p of the relative numbers of neutron and protons, which takes account of the role of the weak interactions pointed out by Hayashi (1950), is close to the modern theory. And Alpher and Herman deserve credit for dealing with Gamow's capricious ways. But the ideas presented in Gamow (1948a,b) were physically sound and prescient steps to our present established ΛCDM cosmology.

The chaotic nature of this story is particularly evident because there were just three main actors, and they were publishing frequently enough that we have easy access to a reasonably detailed record of what they were thinking. I expect that other advances in science, if examined in such close detail, would reveal similar tangled mixes of observational evidence that was variously ignored, or misread, or productive, and of theoretical ideas that were variously wrong, or misunderstood, or remarkably

productive. The cosmology story is particularly unusual, though, because we see the work of an exceptional master of physical intuition, George Gamow.

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