Reports

History of the Universe

Development of the theory of the expanding universe, first proposed by A. Friedmann 55 years ago (*1*), has recently received an encouraging boost from the observational disproval of the steady-state cosmology (*2*) and the unexpected detection of the residual isotropic thermal 3°K radiation (*3*), the existence of which was predicted on the basis of evolutionary cosmology almost two decades ago (*4*).

The purpose of the present report is to give the general description of the time-depending, uniformly curved space and to compare it with the available cosmological information.

The general form of the line-element in the expanding, isotropic, and homogeneous space can be written as (*5*):

$$ds^2 = -\frac{L(t)}{\left[1+\frac{r^2}{4\,\Re_0^2}\right]^2}\,(dr^2 + r^2\,d\theta^2 + r^2\sin^2\theta\,d\phi^2) + dct^2 \qquad (1)$$

where the radius of curvature $\Re_0$ can be positive (closed spherelike space), zero (open Euclidean space), or negative (open saddle-like space).

The time-dependence of the "characteristic length" $L(t)$ is given by (*5*):

$$\frac{1}{L}\frac{dL}{dt} = \left(\frac{8\pi\gamma}{3}\rho - \frac{c^2}{\Re}\right)^{1/2} \qquad (2)$$

where γ is Newton's gravitational constant and ρ the mean (mass) density of the universe. This total mean density ρ can be considered as the sum of the matter density ρ_m and the radiation density ρ_r. Since matter is conserved, we can write quite generally $\rho_m \sim L^{-3}$, except for the very early stages when the particle-antiparticle pairs could be created at the expense of radiation. In the case of thermal radiation one can write quite generally, accepting Wien's law, $\lambda_{max}\,T = \text{const}$, from which follows:

$$\rho_r \sim T_r^4 \sim \lambda^{-4} \sim L^{-4}.$$

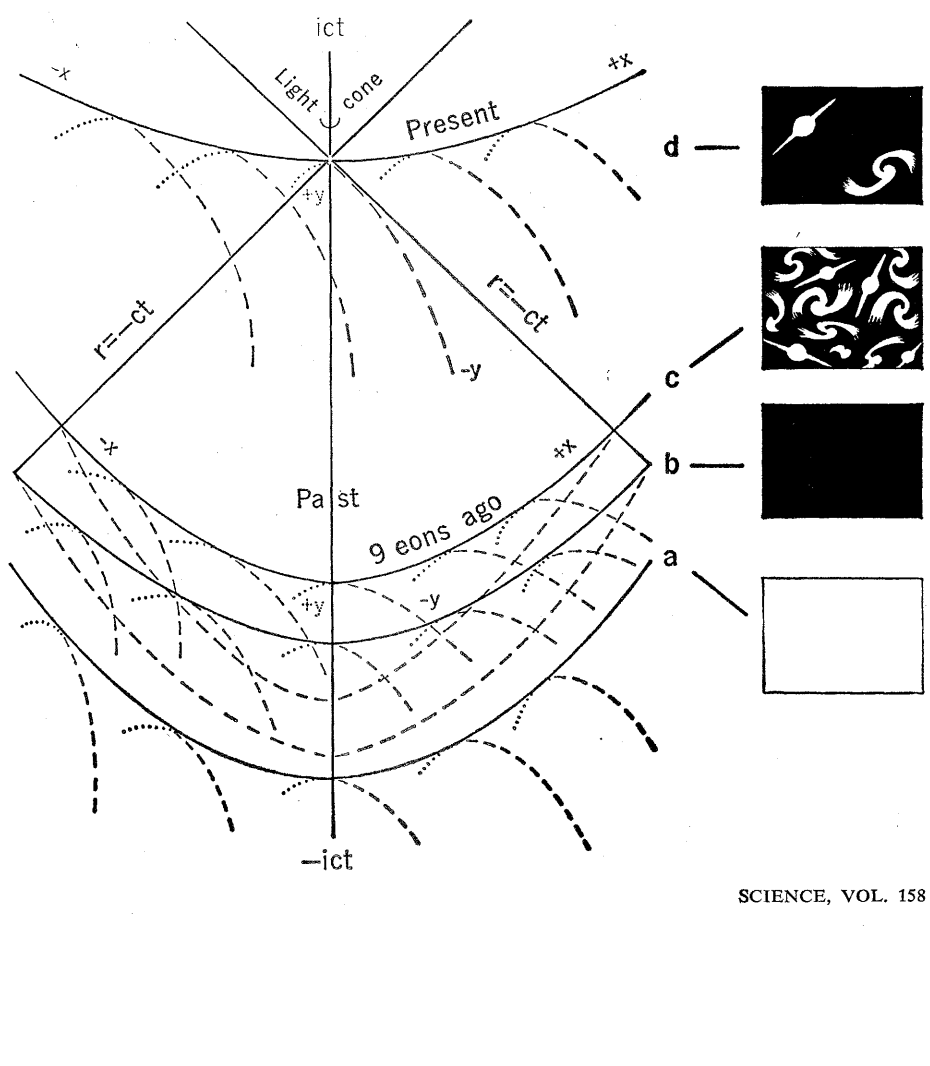
It is interesting to notice that the ratio of the radiation's heat capacity ($c_r = 4aT^3$, where a is Stefan-Boltzmann's constant) to the matter's heat capacity ($c_m = 3/2kn$, where k is Boltzmann's constant and n, particle density) remains constant throughout the entire expansion process except at very early stages where a large number of particle-antiparticle pairs are formed. Using the present values of ρ_m ($\cong 7 \cdot 10^{-31}$ g/cm^3) and ρ_r (for $T = 3$°K), one obtains $c_r/c_m = 10^{10}$. The large value of this pure number is very important for the temporal behavior of the universe, since it guarantees that the changes of the common temperature of space follow the law of adiabatic expansion of radiation ($T \sim L^{-1}$) and not that of matter ($T \sim L^{-2}$).

The meaning of the universal constant 10^{10}, which joins the famous constants 10^{40} and 10^{80}, is not quite clear. Since nucleon-radiation transformations could be expected only in the very early stages of the expansion, it may be connected with the freezing of $2m_p \leftrightarrows 2h\nu$ equilibrium at a very early date.

Substituting into Eq. 2 the present value of Hubble's constant

$$\left[\frac{1}{L}\frac{dL}{dt}\right]_0 = 100 \text{ km sec}^{-1} \text{ Mparsec}^{-1}$$

and the present matter density $7 \cdot 10^{-31}$ g/cm^3, we obtain $\Re_0 = 1.0 \cdot 10^{10} i = 10i$ hubbles, where $i = \sqrt{-1}$. (One *hubble* is defined as 10^9 light-years. Defining one *eon* as 10^9 years, we find that one hubble per eon is the speed of light. One *degree Inferno* (°I) is defined as 10^9°K.) Thus our space is open and limitless but possesses a "horizon" at $r = 2|\Re|$. It can be represented by Minkowski's four-dimensional space-time continuum, as is shown in Fig. 1. (Because of graphic considerations, only two space coordinates, x and y, are shown, and the resulting three-dimensional structure is projected on the flat two-dimensional surface of this magazine's page.)



Correspondence from an Author

September 1, 1967

Dear Phil,

I hope you like the cosmological article which I sent to you 2 days ago. I do not remember whether I mentioned in the accompanying letter that it was written in the Saint Joseph Hospital in Denver where the surgeon very skillfully removed the deposits of calcium carbonate from both carotid arteries in my neck. Well, the increased supply of fresh blood to my brain caused a brainstorm (fortunately not brain stroke), and, the very evening of the day I mailed that letter, I got an idea which, during the 2 days passed, begins to look better and better.

As you know, 30 years ago Dirac wrote a "letter to *Nature*" in which he suggested that the ratio of electrostatic and gravitational forces $e^2/\gamma mM$ between a proton and an electron (γ, Newton's constant), which has a numerical value about 10^{40}, must be not a constant but the age of the universe expressed in tempons (10^{-23} second). Hence, said Dirac, the gravitational constant must change in inverse proportion to cosmic time. The first criticism of this idea was made by Bohr. I still remember him coming to my room (I was visiting Copenhagen at that time), with the fresh issue of *Nature* in his hands, saying: "Look what happens to people when they get married." (At that time Dirac was freshly married to Wigner's sister.) A more serious criticism was made by Teller (in Washington at that time) who has shown that if $\gamma \sim t^{-1}$, the brightness of the Sun $L \sim \gamma^7 \sim t^{-7}$, and the distance Sun-Earth $r \sim \gamma^{-1} \sim t$. Thus, the temperature of the Earth

$$T\oplus \sim \left(\frac{t^{-7}}{t^{-2}}\right)^{1/4} \sim (t^{-9})^{1/4} \sim t^{-2.25}$$

and the Cambrian oceans would be boiling (with the old value 1.8 eons for the age of the universe).

Well, when the age was brought up to 9 eons, Edward's argument lost strength, but now it is good again after (according to *Science*) one found algae at 3.1 eons ago. Another argument, without reference to paleontology was used 3 years ago by Martin Schwarzschild, and quite recently by myself without knowing that he did it before. Martin used an electronic computer [*Astrophys. J.* **139**, 587 (1963)] and I used simple homology transformations. Well, the old horse is dead, so why kick it again. But I was very unhappy because Dirac's idea was so elegant. Thus, 48 hours ago, I told myself: "If decreasing γ does not work, why not to keep it constant and make e^2 to increase $\sim t$ instead?" The main question was how the surface temperature of the Earth will behave in the case? Fortunately, I could answer it easily. If you look at formula 8 of my paper [*Proc. Nat. Acad. Sci. U.S.* **57**, 187 (1967)], you will find that the luminosity of the Sun changes as

$$\kappa^{-(2n+6)/(2n+6)} = \kappa_0^{-1} \text{ (for } n \rightarrow \infty)$$

According to Kramers' opacity formula:

$$\kappa_0 \sim \frac{e^6}{m^2c^4h} \sim (e^2)^3 \sim t^{-3}$$

Fig. 1 (opposite page). A schematic presentation of Minkowski's world corresponding to the expanding space (here two-dimensional) with negative curvature. The intersections of the light cone with different saddle-shaped surfaces represent the "world picture" as seen "now" from "here." (a) Corresponds to the early hot stage with the temperature running into many degrees Inferno. Light elements are formed here. This region is seen from "now, here" as 3°K radiation with the wavelength expanded from the original hard γ-radiation to the short radio waves; (b) represents the stage of the cooling, nonluminous plasma; (c) shows the formation of dark protogalaxies and the condensation of stars; and (d) demonstrates the dispersal of the galaxies beyond the point of return.

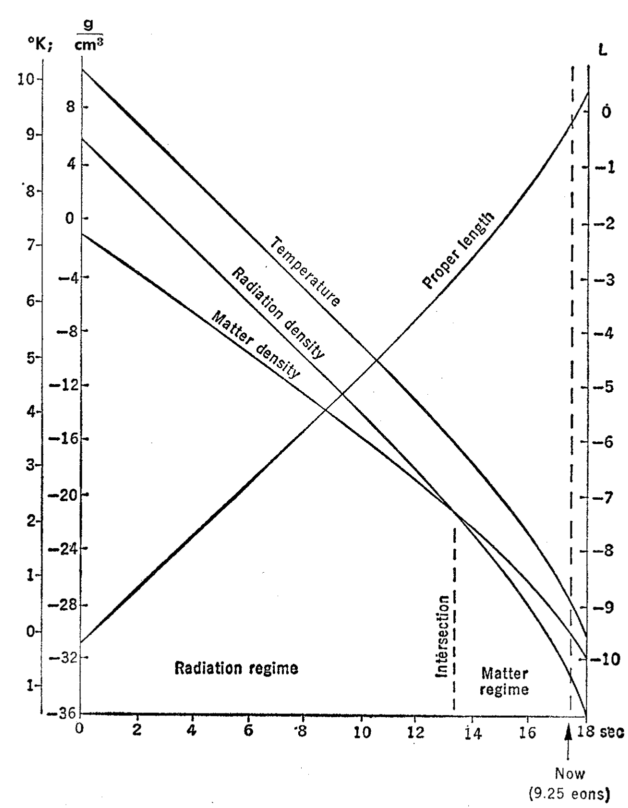
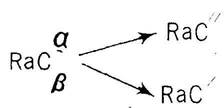


Fig. 2 (right). Physical conditions of the universe from $t = 1$ sec to $t = 9.25$ eons (after Alpher, Gamow, and Herman). Analytical solutions are based on the boundary conditions: $H_{\text{present}} = 100$ km sec^{-1} Mparsec^{-1}; $\rho_{\text{matter present}} = 7 \cdot 10^{-31}$ g/cm^3; $T_{\text{present}} = 3$°K.

Since the distance Sun-Earth does not change,

$$T_{\oplus} \sim (t^{-3})^{1/4} \sim t^{-3/4}$$

Thus, 3 eons ago (⅓ of the total age) the oceans were just close to boiling. And, of course, the argument based on total nuclear energy supply also loses force. The Sun could have existed 5 eons (but not 9!). Now, you see, the thing has quite a lot of implications. How could we notice smaller value of elementary charge in the past? Of course the Rydberg ($\sim e^4$) constant must have been smaller, and the spectral lines red-shifted. But the effect cannot be distinguished from Doppler shift due to expansion. Maybe the large red shifts in quasars (I prefer the name qualaxies) is part recession, part smaller e^2 in the past. But, if one could observe the fine structure of H-lines in distant galaxies, then, of course, my hypothesis can be proved or disproved. But this is up to Mt. Wilson and Palomar people to decide. Maybe one can if one sends a good parabolic mirror and spectrograph (echelon) into the orbit. From the geological point of view one would expect that α-decay rates were faster in the past. It seems to me that the best chance to check this is by studying the pleochroic haloes in old micas and fluorspars [Rutherford, Chadwick, Ellis, *Radiations from Radioactive Substances* (Cambridge Univ. Press, 1930), p. 180]. One should study the forking in C product like



Since λ_α and λ_β probably have different time dependence, I see that in:

Probability of decay

	α	β	λ_α	λ_β
RaC	0.04%	99.96%	$1.34 \cdot 10^{-7}$	$5.92 \cdot 10^{-4}$
ThC	3.5 %	65 %	$5.1 \cdot 10^{-5}$	$1.23 \cdot 10^{-4}$
AcC	99.68%	0.32%	$4.79 \cdot 10^{-3}$	$1.6 \cdot 10^{-5}$

If $\lambda_\alpha / \lambda_\beta$ changes with time then in the old haloes the intensity of rings of C α-particles must be widely different. Could be done. I remember hearing that the best collection was in a museum in Halifax (Nova Scotia).

Well, I feel somewhat stupid; like a man who inherited $\$10^6$. What does one do with it? Well, one can do something. At least it is very amusing.

I started writing this as a cover-letter for an article. But I find that I have already written it. It seems that all is quite logical and not nonsense. A few people here whom I told about it agree that it looks sensible, and that it is a good idea to tell about it.

Yours,
George Gamow

September 25, 1967

Dear Phil,

When you telephoned me a few days after receiving my letter about e changing with the age of the universe, you asked me whether I still believe it. I answered "yes," and so I hasten now to tell you that I do not believe it any more since last Friday. In my letter to *Phys. Rev. Letters* which appears today, I suggested that the astronomers should measure the fine-structure separation in the absorption spectra of "quasars" since this separation goes as e^8 as compared with e^6 for the ordinary lines of the spectrum. In suggesting it, I did not really believe that this can be done, since I thought that the absorption lines in this case are very wide so that no fine structure could be noticed. Last Friday I picked up the July 1967 issue of *Astrophys. J.* which was sitting on my desk for about a month, and found a paper of Maarten Schmidt *et al.* who just did that. They write, "We find that: $\alpha_{z=1.95}/\alpha_{z=0} = 0.97$, 0.94 and 1.01 (for three Si doublets). We conclude that: $\alpha_{z=1.95}/\alpha_{z=0} = 0.98 \pm 0.05$." Since $z + 1 = 2.95$, the separation of the lines in "quasar" should be 3 times smaller than in the lab. source!

Thus, α *does not* depend on time, and $e^2/\gamma m M = 10^{36}$ = const! The coincidence of this 10^{36} with the age 10^{36} of the universe in tempons is a coincidence! (Dirac used the mass of an electron and the mass of a proton. Here both masses are those of protons.) And $e^2/\gamma m M = 10^{36}$ is *inexplainable* unless one answers that the God invented it in His own head! It is very discouraging since any good theoretical physicist has a strong belief that any numerical coefficient should be explained as a mathematical number. But, as Comrade Lenin wrote once, "the facts are stubborn things." But, from my bewilderment about the slenderness of the absorption lines, came a very encouraging result. To understand it, let us calculate the "free path" of a light-ray through the space of the universe.

Assuming, very roughly, that the galaxies are spaced about 10^6 light-years apart, and that their diameters are 10^{-2} of their mutual separation, we find that the free path is $(10^2)^2 \cdot 10^6 = 10^{10}$ l.y. This means that the heaven is plastered with galaxies, and that light from a source (with continuous spectrum) located at 10^{10} l.y. will almost certainly pass through a body of at least one galaxy located somewhere between the source and ourselves. The observed absorption lines are therefore not much different from the familiar gas-cloud absorption lines in the spectra of the distant stars of our Milky Way. I am alerting Palomar astronomers to look for "quasars" with two sets of absorption lines shifted in respect to each other. Now, the mysterious variability of "quasars" is not much different from the twinkling of stars. To have a very distant source twinkle, it must be very small (in angle). But how small is a point? One can guess that, to have the observed "period" of a few months, the small luminous disk (moving at 10^3 or 10^4 km/sec) must cover its own diameter in a few months. Thus $D \cong 10^{15}$ cm, and if the mass is that of a galaxy the mean density is 10^{-3}. To be some 10 or 100 times brighter than the galaxy, the surface temperature must be some 10^5°K. Thus I sing:

"Twinkle, twinkle QuasiStar,
Now I know what you are."

Thus be it concluded, that, if you still plan to publish my first letter to you put these two letters together.

Yours,
George Gamow

Equation 2 can be integrated analytically and, using as the boundary condition the present values of Hubble's constant, matter density, and radiation temperature, one obtains the curves shown in Fig. 2, which represent the physical conditions in the universe all the way back to the first seconds of its existence (*6*).

There were two important periods in the history of the expanding universe. The first 30 minutes after the singularity at the moment of the origin were responsible for the formation of light elements as a result of thermonuclear reactions in the primeval *ylem* (that is, a mixture of protons, neutrons, electrons, and, above all, light quanta). The pioneering work in this direction was carried out by Fermi and Turkevich (*7*), who integrated the equations of thermonuclear reaction in light nuclei for the variable temperatures and densities corresponding to the early periods of expansion. Their calculations have shown that the ratio of hydrogen to helium at the end of the reaction period is expected to be about 50:50, in reasonable agreement with the observed values. On the other hand, due to the absence of reasonably stable nuclei of mass 5, the amounts of lithium and all other heavier elements came out too small by a factor of about 100, as compared with the astronomical data for the sun and stars. Recently the calculations of Fermi and Turkevich were repeated more exactly by Wagoner, Fowler, and Hoyle (*8*), who used modern values for the cross sections of various nuclear reactions and the electronic computer for obtaining the curves of growth. These new calculations generally confirmed the conclusions of the earlier ones, leading to a result that heavy elements could not have been formed during the early stages of the expanding universe, but must be attributed to the vast stellar explosions (supernovae) of the early history of the universe (*9*). This double attitude is, however, quite acceptable since the recent progress of astronomical knowledge has shown that the earlier assumption of the chemical homogeneity of the universe is not quite correct. In fact, while the stars of Baade's Population I contain comparatively large amounts (up to 1 percent) of the heavier elements, the amounts of these elements in the stars of Population II is, at least, a hundred times smaller. It is generally agreed that the stars of Population II represent the original stock of stars, while the stars belonging to Population I may be formed by the recondensed material of the supernovae which exploded early in the history of the universe. Thus it is quite likely that, whereas in the former case we have agreement with the Fermi-Turkevich and later calculations, in the latter case the stars are enriched by the material synthesized in the preceding supernovae.

The second interesting period in the history of the universe is around t = 1.0 millieons where we have: $\rho_r = \rho_m = 5 \cdot 10^{-22}$ g/cm^3 and T = 3000°K, which corresponds to the transition of the expanding universe from the radiation regime to the matter regime. The early attempts (*10*) to get the correct sizes and masses of protogalaxies by using Jeans's formula for the gravitational instability were all leading to the mass values of protogalaxies that were too small by about three orders of magnitude. The change of scale, and the use of better temperature and density curves, did not help the situation, and the problem is still open. One obvious improvement would be to use in the Jeans's formula, not the mean thermal velocity of particles as is usually done, but what can be called an "effective velocity" which represents the velocity on the tail of the Maxwell's distribution, for which the evaporation rates of the condensations are sufficiently small, as compared with the rate of their separation, resulting from the expansion of space. Another important factor, which was not previously taken into account, is the role of thermal radiation, the mass density of which is comparable to that of matter. In particular, the transition of ionized hydrogen and helium into their neutral forms takes place for the temperatures characteristic for this period of the history of the universe. If everything fails, there is still the possibility that the supersonic turbulence of the primordial gas would be of some help. But we shall see.

GEORGE GAMOW

Department of Physics and Astrophysics, University of Colorado, Boulder

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31 August 1967

Atmospheric Burnup of a Plutonium-238 Generator

Abstract. *The stratospheric inventory of the plutonium-238 resulting from the disintegration of a nuclear auxiliary power generator (SNAP-9A) in early 1966 accounts for essentially all the plutonium present in the original generator that reentered the atmosphere. Consequently, the pyrophoric* ^{238}*Pu must have completely burned up during reentry and ablated into small particles. The arithmetic mean of the distribution of the* ^{238}*Pu particle size was estimated to be 10 millimicrons, which confirms this conclusion.*

On 21 April 1964, a navigational satellite employing a SNAP-9A generator (Systems for Nuclear Auxiliary Power) did not reach orbital velocity because of a rocket failure after launch. The SNAP-9A generator is a nuclear-fueled power package which converts the heat developed by a radioactive source into electrical energy, contains about 17 kilocuries of ^{238}Pu and weighs 12.3 kg (*1*). Since ^{238}Pu is a highly toxic nuclide, and since bone is the critical organ for soluble plutonium and lung for insoluble plutonium, considerable interest was exhibited in the ultimate fate and disposition of the ^{238}Pu.

Korsmayer (*2*) estimated that the satellite entered the atmosphere at about 150,000 feet (46 km or 46,000 m) over the Indian Ocean in the Southern Hemisphere. There are three alternatives as to what could have happened when the SNAP-9A reentered the atmosphere. One is that it plunged intact into the Indian Ocean leaving little or no remnants in the atmosphere. A second is that the heat of reentry into the atmosphere completely consumed the device and the pyrophoric ^{238}Pu ablated into small particles. The third alternative is some combination of the