History of the 2.7 K Temperature Prior to Penzias and Wilson

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We present the history of estimates of the temperature of intergalactic space. We begin with the works of Guillaume and Eddington on the temperature of interstellar space due to starlight belonging to our Milky Way galaxy. Then we discuss works relating to cosmic radiation, concentrating on Regener and Nernst. We also discuss Finlay-Freundlich's and Max Born's important research on this topic. Finally, we present the work of Gamow and collaborators. We show that the models based on a Universe in dynamical equilibrium without expansion predicted the 2.7 K temperature prior to and better than models based on the Big Bang.

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1. Introduction

In 1965 Penzias and Wilson discovered the Cosmic Background Radiation (CBR) utilizing a horn reflector antenna built to study radio astronomy (Penzias and Wilson 1965). They found a temperature of 3.5 ± 1.0 K observing background radiation at 7.3 cm wavelength. This was soon interpreted as a relic of the hot Big Bang with a blackbody spectrum (Dicke *et al.* 1965). The finding was considered a proof of the standard cosmological model of the Universe based on the expansion on the Universe (the Big Bang), which had predicted this temperature with the works of Gamow and collaborators.

In this paper we show that other models of a Universe in dynamical equilibrium without expansion had predicted this temperature prior to Gamow. Moreover, we show that Gamow's own predictions were worse than these previous ones.

Before beginning let us list briefly some important historical information which help to understand the findings. Stefan found experimentally in 1879 that the total bolometric flux of radiation F emitted by a black body at a temperature T is given by $F = \sigma T^4$, where σ is now called Stefan-Boltzmann's constant (5.67×10^{-8} $\mathrm{Wm^{-2}K^{-4}}$). The theoretical derivation of this expression was obtained by Boltzmann in 1884. In 1924 Hubble established that the nebulae are stellar systems outside the Milky Way. In 1929 he obtained the famous redshift-distance law.

2. Guillaume and Eddington

The earliest estimation of a temperature of "space" known to us is that of Guillaume (1896). It was published in 1896, prior to Gamow's birth (1904). Here we quote from this paper (English translation by C. Roy Keys):

> *"Captain Abney has recently determined the ratio of the light from the starry sky to that of the full Moon. It turns out to be 1/44, after reductions for the obliqueness of the rays relative to the surface, and for atmospheric absorption. Doubling this for both hemispheres, and adopting 1/600000 as the ratio of the light intensity of the Moon to that of the Sun (a rough average of the measurements by Wollaston, Douguer and Zöllner), we find that the Sun showers us with 15,200,000 time more vibratory energy than all the stars combined. The increase in temperature of an isolated body in space subject only to the action of the stars*

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will be equal to the quotient of the increase of temperature due to the Sun on the Earth's orbit divided by the fourth root of 15,200,000, or about 60. Moreover, this number should be regarded as a minimum, as the measurements of Captain Abney taken in South Kensington may have been distorted by some foreign source of light. We conclude that the radiation of the stars alone would maintain the test particle we suppose might have been placed at different points in the sky at a temperature of 338/60 = 5.6 abs. = 207º.4 centigrade. We must not conclude that the radiation of the stars raises the temperature of the celestial bodies to 5 or 6 degrees. If the star in question already has a temperature that is very different from absolute zero, its loss of heat is much greater. We will find the increase of temperature due to the radiation of the stars by calculating the loss using Stefan's law. In this way we find that for the Earth, the temperature increase due to the radiation of the stars is less than one hundred-thousandth of a degree. Furthermore, this figure should be regarded as an upper limit on the effect we seek to evaluate."

Of course, Guillaume's estimation of a 5-6 K blackbody temperature may not have been the earliest one, as Stefan's law had been known since 1879. Moreover, it is restricted to the effect due to the stars belonging to our own galaxy.

We now quote from Eddington's book, *The Internal Constitution of the Stars* (1988), published in 1926. The last chapter of this book is called "Diffuse Matter in Space" and begins discussing "The Temperature of Space:"

Chapter XIII
DIFFUSE MATTER IN SPACE
The Temperature of Space.

256. *The total light received by us from the stars is estimated to be equivalent to about 1000 stars of the first magnitude. Allowing an average correction to reduce visual to bolometric magnitude for stars of types other than F and G, the heat received from the stars may be taken to correspond to 2000 stars of apparent bolometric magnitude 1.0. We shall first calculate the energy-density of this radiation.*

A star of absolute bolometric magnitude 1.0 radiates 36.3 times as much energy as the sun or 1.37×10^{35} *ergs per sec. This gives* 1.15×10^{-5} *ergs per sq. cm. per sec. over a sphere of 10 parsecs (*3.08×10^{19}*cm.) radius. The corresponding energy-density is obtained by dividing by the velocity of propagation and amounts to* 3.83×10^{-16} *ergs per cu. cm. At 10 parsecs distance the apparent magnitude is equal to the absolute magnitude; hence the energy-density* 3.83×10^{-16} *corresponds to apparent bolometric magnitude 1.0.*

Accordingly the total radiation of the stars has an energy-density

$$2000\times3.83\times10^{-16}=7.67\times10^{-13}\ ergs/cm^3.$$

By the formula $E=sT^4$ *the effective temperature corresponding to this density is*

$$3^{\circ}.18 \text{ absolute.}$$

In a region of space not in the neighbourhood of any star this constitutes the whole field of radiation, and a black body, e. g. a black bulb thermometer, will there take up a temperature of $3^{\circ}.18$ *so that its emission may balance the radiation falling on it and absorbed by it. This is sometimes called the 'temperature of interstellar space.'*

One important aspect to emphasize here is that Eddington's estimation of a temperature of 3.18 K was not the first one, as Guillaume had obtained a similar figure by 30 years earlier. Although Eddington did not quote Guillaume or any other author, it is clear that he was here following someone's else derivation. This is indicated by the sentences "The total light received by us from the stars is estimated [by whom?] to be..." and "This is sometimes called [by whom?] the 'temperature of interstellar space.' " These sentences show that others had also arrived at this result. It is very probable that in the fifty years between Stefan's law (1879) and Eddington's book (1926) others arrived at the same conclusion independent of Guillaume's work (1896).

Another point to bear in mind is that Eddington and Guillaume were discussing the temperature of interstellar space due to fixed stars belonging to our own galaxy, and not of intergalactic space. Remember that Hubble only established the existence of external galaxies beyond doubt in 1924.

3. Regener

Cosmic rays were discovered in 1912 by V. F. Hess (Rossi 1964). He made a balloon flight and observed that a charged electroscope would discharge faster at high altitudes than at the sea level, contrary to expectations. This discharge is due to the ionization of the air, which was shown to increase with altitude. It was known that radiation emitted by radioactive substances ionized the air, and Hess's measurements showed that the radiation responsible for the natural ionization of air entered the atmosphere from above, and not from the ground.

In 1928 R. A. Millikan and Cameron (1928) found that the total energy of cosmic rays at the top of the atmosphere was one-tenth of that due to starlight and heat. In 1933 E. Regener (1933) concluded that both energy fluxes should have essentially the same value. This is a very important result with far reaching cosmological implications: It indicates that the energy density of starlight due to our own galaxy is in equilibrium with the cosmic radiation, which for the most part is of extragalactic origin. It has always been difficult to know exactly the origin of the cosmic rays, but the fact that a major part of its components originated outside our galaxy was inferred from another measurement of Millikan and Cameron

(1928). In this work they showed that the intensity of the radiation coming from the plane of the Milky Way was the same as that coming from a plane normal to it. This isotropy clearly indicated an extragalactic origin.

Regener's work in general has been described briefly by Rossi (1964) as follows:

> *In the late 1920s and early 1930s the technique of self-recording electroscopes carried by ballons into the highest layers of the atmosphere or sunk to great depths under water was brought to an unprecedented degree of perfection by the German physicist Erich Regener and his group. To these scientists we owe some of the most accurate measurements ever made of cosmic-ray ionization as a function of altitude and depth.*

In his work of 1933, Regener says the following (we are here replacing the term *Ultrastrahlung* - ultraradiation - which Regener and others utilized at that time by the expression "cosmic radiation," as this radiation is called nowadays):

> *However, the density of energy produced by cosmic rays, which is nearly equal to the density of light and heat emitted by the fixed stars, is very interesting from an astrophysical point of view. A celestial body with the necessary dimensions to absorb the cosmic rays—in case of a density of 1, a body with a diameter of several meters (5 meters of water absorb $\frac{9}{10}$ of the cosmic rays)—will be heated by cosmic rays. The increase in temperature will be proportional to the energy of absorbed cosmic rays (S_U) and the surface (O). The temperature of the body will increase until the heat it emits—in case of black body radiation $s \cdot T^4 \cdot O$— reaches the same value. We then obtain a final temperature of $T = \sqrt[4]{S_U / s}$. Substituting numerical values we obtain 2.8 K*

This, according to Regener (1933), would be the temperature characteristic of intergalactic space, since in this region the light and heat from any galaxy would be negligible.

4. Nernst

The work of Regener was discussed by the famous physicist Walther Nernst (1864-1941) who received the Nobel prize for chemistry in 1920 for his third law of thermodynamics (1906). By 1912 Nernst had developed the idea of an Universe in a stationary state. He expressed this idea in simple terms in 1928: "The Universe is in a stationary condition, that is, the present fixed stars cool continually and new ones are being formed" (Nernst 1928). In 1937 he developed this model and proposed a tired light explanation of the cosmological redshift, namely, the absorption of radiation by the luminiferous ether, decreasing the energy and frequency of galactic light (Nernst 1937). This would not be due to a Doppler effect according to Nernst. In this work Nernst also mentions Regener's important paper discussed above.

The following year Nernst (1938) published another paper discussing the radiation temperature in the Universe. Here he arrived at a temperature in intergalactic space as 0.75 K. Once more he discusses Regener's work and asserts that the cosmological redshift is not due to a Doppler effect.

In the works of Eddington, Regener, Nernst and others to follow, it is important to stress the utilization of Stefan-Boltzmann's law, which is characteristic of a black body radiation. Another point to be noted is that the energy densities of these radiations (due to star light and cosmic rays, for instance) have been measured to have the same value, indicating a situation of dynamical equilibrium. Sciama describes this situation as follows (Sciama 1971):

> *The cosmic ray flux almost certainly fills the Milky Way, and corresponds to an energy density in interstellar space of about* $1\ eVcm^{-3}$ (10^{-12} $erg\ cm^{-3}$). *This is comparable with the energy density of starlight, the turbulent kinetic energy density of the interstellar gas and, as we shall see later, the energy density of the interstellar magnetic field. This is the basis of our statement that the cosmic rays are dynamically important. They constitute a relativistic gas whose energy and pressure cannot be ignored. The near-equality of the various energy densities is probably no accident, but despite many attempts a full understanding of it has not yet been achieved.*

And again on p. 185, after mentioning Penzias and Wilson's discovery of a blackbody radiation of 3 K:

> *From a laboratory point of view 3 K is a very low temperature. Indeed to measure it the microwave observers had to use a reference terminal immersed in liquid helium. Nevertheless from an astrophysical point of view 3º K is a very high temperature. A universal black body radiation field at this temperature would contribute an energy density everywhere of* $1\ eVcm^{-3}$. *As we saw in chapter 2 [p. 25] this is just the energy density in our Galaxy of the various modes of interstellar excitation—starlight, cosmic rays, magnetic fields and turbulent gas clouds. So even in our Galaxy the cosmological background radiation would be for many purposes as important as the well-known energy modes of local origin.*

We would like to make two remarks here. The first is that the main part of the cosmic radiation may have an extragalactic origin (see the comment on the work of Millikan and Cameron above), as may the magnetic fields which fill all space. If this is the case, then three extragalactic modes of excitation (the cosmic ray flux, magnetic fields and the CBR) would be in thermal equilibrium with one another and with energy fields generated inside our own galaxy, such as starlight and turbulent gas clouds. The easiest way to understand this fact is to conclude that the Universe as a whole is in a state of dynamical equilibrium.

5. McKellar and Herzberg

Here we would like to mention briefly the work of Herzberg in 1941 (based on observations made by A. McKellar) discussing cyanogen measurements in interstellar space. Herzberg found a temperature of 2.3 K characterizing the observed degree of excitation of the CN molecules if they were in equilibrium in a heat bath (Herzberg):

> *The observation that in interstellar space only the very lowest rotational levels of* CH, CH^+, and CN *are populated is readily explained by the depopulation of the higher levels by emission of the far infrared rotation spectrum (see p. 43) and by the lack of excitation to these levels by collisions or radiation. The intensity of the rotation spectrum of CN is much smaller than that of CH or* CH^+ *on account of the smaller dipole moment as well as the smaller frequency [due to the factor* n^4 *in (I, 48)]. That is why lines from the second lowest level (K = 1) have been observed for CN. From the intensity ratio of the lines with K = 0 and K = 1, a rotational temperature of 2.3 K follows, which has of course only a very restricted meaning.*

Obviously there is a great meaning in this result, although it was not recognized by Herzberg. This is discussed by Sciama (1971). It should only be stressed that once more, this result was not obtained utilizing the Big Bang cosmology.

6. Finlay-Freundlich and Max Born

In 1953-4 Finlay-Freundlich (1953, 1954a,b)proposed a tired light model to explain the redshift of solar lines and some anomalous redshifts of several stars, as well as the cosmological redshift. He proposed a redshift proportional to the fourth power of the temperature, and his work was further analysed by Max Born (1953, 1954). His formula is as follows: $\Delta n / n = -AT^4 l$, where Δn is the change in frequency of the line, n its original frequency, A is a constant, T the temperature of the radiation field and l the length of path traversed through the radiation field. What matters to us here is his discussion (1954b) of the cosmological redshift:

> *§ 6. The Cosmological Red Shift*
>
> *The fundamental character of the effect under consideration raises, necessarily, the question whether it might not also be the cause of the cosmological red shift which hitherto has been interpreted as a Doppler effect. In this case, the influence of the factor l in formula (1) is given explicitly from observations. The observed red shift* $\Delta l / l$ *increases for every million parsec* $(= 3 \times 10^{24}\ cm)$ *by* 0.8×10^{-3} *which corresponds to a velocity increase of 500 km/sec when interpreted as a Doppler effect. An increase by 10 km/sec—corresponding to the red shift in a B2 star with* $T_B = 20000\ K$ *—would correspond to a path* $l_S = 1.2 \times 10^{23}\ cm$.
>
> *As far as the mean temperature* T_S *of intergalactic space is concerned, apart from the knowledge that it must be near the absolute zero, no reliable information is available. If we may interpret the cosmological red shift in the same way as the stellar red shifts, the following equation should hold:*
>
> $$T_S^4 l_S = T_B^4 l_B \text{ , or } T_S = T_B (l_B / l_S)^{1/4} \text{ . } \quad (3)$$
>
> *"Equation (3) shows that the value of* T_S *obtained in this way does not depend strongly on the choice of* l_B *. Taking for* l_B *the two extreme values* 10^7 cm *and* 10^9 cm*, we get the following two reasonable values*
>
> $$T_S = 1.9 K \quad \text{and} \quad T_S = 6.0 K.$$
>
> *In a recent paper Gamow (1953) [Gamow, G., 1953,* Dan. Acad. Math.-Phys. Section, ***27****, No. 10] derives a value for* T_S *of 7 K from thermodynamical considerations assuming a mean density of matter in space of* $10^{-30}\ g / cm^3$.
>
> *One may have, therefore, to envisage that the cosmological red shift is not due to an expanding Universe, but to a loss of energy which light suffers in the immense lengths of space it has to traverse coming from the most distant star systems. That intergalactic space is not completely empty is indicated by Stebbins and Whitford's discovery (1948) [Stebbins, J., and Whitford, A. E., 1948,* Ap. J., *108, 413] that the cosmological red shift is accompanied by a parallel unaccountable excess reddening. Thus the light must be exposed to some kind of interaction with matter and radiation in intergalactic space.*

The main points to emphasize here are that Finlay-Freundlich proposed an alternative to the Doppler interpretation of the cosmological redshift and arrived at 1.9 K < T < 6.0 K for the temperature of intergalactic space. This is quite remarkable.

It is important to quote here Max Born (1954) when discussing Finlay-Freundlich's proposal that this new effect might be due to a photon-photon interaction, namely :

> *An effect like this is of course not in agreement with current theory. It has, however, an attractive consequence. A simple application of the conservation laws of energy and momentum shows that a collision of this kind is only possible if a pair of particles with opposite momenta is created. The energy of one of these is* $hn' = -hdn / 2$, *where* dn *is given by (6)* [$dn = -Cn\bar{n} / n_o$]. *If the secondary particles are photons their frequency is of the order of radar waves*

(for the sun $n' \sim 2\times10^{9}\sec^{-1}$, $l' \sim 15cm$). Thus the red-shift is linked to radio-astronomy.

We need only remember here the work of Penzias and Wilson 11 years later with a horn antenna built to study radio waves which found the CBR with a characteristic wavelength of 7 cm... This must be considered a highly successful prediction by Max Born!

7. Gamow and Collaborators

As we have seen, Finlay-Freundlich (1954b) mentioned that Gamow had derived the value of 7 K for intergalactic space in 1953. Prior to this work we could only find two other papers where there was a prediction of this temperature by Gamow's collaborators Alpher and Herman (1948, 1949). In the first of these works they said: "The temperature of the gas at the time of condensation was 600 K., and the temperature in 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."

In the second of these works, where the present the details of these calculations, they said the following (our emphasis in bold):

In accordance with eq. (4) [$r_r r_m^{-4/3} = constant$], the specification of r_m'', r_m', and r_r' fixes the present density of radiation, r_r''. In fact, we find that the value of r_r'' consistent with eq. (4) is

$$r_r'' \cong 10^{-22}\ g/cm^3 , \qquad (12d)$$

which corresponds to a temperature now of the order 5 K**. This mean temperature for the Universe is to be interpreted as the background temperature which would result from the universal expansion alone. **However, the thermal energy resulting from the nuclear energy production in stars would increase this value."

From this it is evident that their prediction in 1948 was $T \approx 5K$ and in 1949 they obtained a temperature greater than 5 K, although close to this value.

The only other prediction of this temperature by Gamow known to us prior to Penzias and Wilson discovery (beyond that of 7 K in 1953) was published by Gamow (1961) in his book *The Creation of the Universe*. The first edition of this book is from 1952, and here we quote from the revised edition of 1961, only four years before Penzias and Wilson. In this book there is only one place where he discusses the temperature of the Universe, namely [21, p. 42, our emphasis in bold]:

The relation previously stated between the value of Hubble's constant and the mean density of the Universe permits us to derive a simple expression giving us the temperature during the early stages of ex pansion as the function of the time counted from the moment of maximum compression. Expressing that time in seconds and the temperature in degrees (see Appendix, pages 142-143), we have:

$$temperature = \frac{1.5\times10^{10}}{[time]^{1/2}}$$

*Thus when the Universe was 1 second old, 1 year old, and 1 million year old, its temperatures were 15 billion, 3 million, and 3 thousand degrees absolute, respectively. **Inserting the present age of the univserse ($t = 10^{17}$ sec) into that formula, we find***

$$T_{present} = 50 \text{ degrees absolute}$$

which is in reasonable agreement with the actual temperature of interstellar space. Yes, our Universe took some time to cool from the blistering heat of its early days to the freezing cold of today!

We discuss these predictions by Gamow and collaborators below.

8. Discussion and Conclusion

In most textbooks nowadays we see the statement that Gamow and collaborators predicted the 2.7 K temperature prior to Penzias and Wilson, while the steady-state theory of Hoyle, Narlikar and Gold did not predict this temperatu re. Therefore the correct prediction of the 2.7 K is hailed as one of the strongest arguments in favour of the Big Bang. However, these two models have one very important aspect in common: both accept the interpretation of the cosmological redshift as being due to a Doppler effect, which means that both models accept the expansion of the Universe.

But there is a third model of the Universe which has been developed in this century by several scientists including Nernst, Finlay-Freundlich, Max Born and Louis de Broglie (1966). It is based on a Universe in dynamical equilibrium without expansion and without continuous creation of matter. We reviewed this subject in earlier papers (Assis 1992, 1993). Although it is not considered by almost any textbook dealing with cosmology nowadays, this third model proves to be the most important one of all of them.

In order to understand how the textbooks could neglect equilibrium cosmology so completely, it is worthwhile to quote a letter sent by Gamow to Arno Penzias, in 1965 after Penzias and Wilson's discovery (curiously the letter was dated 1963...). This letter was reproduced in Penzias's article (1972), from which we quote:

Thank you for sending me your paper on 3 K radiation. It is very nicely written except that "early history"is not "quite complete". The theory of, what is now known, as, "primeval fireball", was first developed by me in 1946 (Phys. Rev. 70 , 572, 1946; 74, 505, 1948; Nature 162, 680, 1948). The prediction of the numerical value of the present (residual) temperature could be found in Alpher & Hermann's paper (Phys. Rev. 75, 1093, 1949) who estimate it as 5 K, and in my paper (KongDansk. Ved. Sels 27 nº 10, 1953) with the estimate of 7 K. Even in my *popular book* Creation of the Universe *(Viking 1952) you can find (on p. 42) the formula* $T = 1.5 \times 10^{10} / t^{1/2}\ K$*, and the upper limit of 50 K. Thus, you see the world did not start with almighty Dicke.*

Sincerely,
G. Gamow

This letter, as we have seen, does not correspond to the true facts. Gamow, in the revised edition of his book of 1952, published in 1961, calculated a temperature. Thus, in this work Gamow did not estimate an *upper limit of 50 K.* The need for Gamow to convince everybody that he had predicted correctly, and before everyone else, the temperature of the cosmic background radiation is evident from another part of Penzias's paper (1972):

It is beyond the scope of this contribution to weigh the various theoretical explanations of the 3 K. Still the unique claim of the hot evolving Universe theory is that it predicted the background radiation before the fact. At the 4th "Texas" Symposium on Relativistic Astrophysics, George Gamow was the chairman of the session on Microwave Background Radiation. He ended his remarks with a comment which, to the best of my recollection, went, "If I lose a nickel, and someone finds a nickel, I can't prove that it's my nickel. Still, I lost a nickel just where they found one." The applause was loud and long.

As we have seen in this paper, Gamow and collaborators obtained from $T \approx 5$ K to T = 50 K in monotonic order (5 K, ≥ 5 K, 7 K and 50 K)... These are quite poor predictions compared with Guillaume, Eddington, Regener and Nernst, McKellar and Herzberg, Finlay-Freundlich and Max Born, who arrived at, respectively: 5 K < T < 6 K, T = 3.1 K, T = 2.8 K, T = 2.3 K, 1.9 K < T < 6.0 K! All of these authors obtained these values from measurement and or theoretical calculations, but none of them utilized the Big Bang. This means that the discovery of Penzias and Wilson cannot be considered decisive evidence in favour of the Big Bang. Quite the contrary, as the models of a Universe in dynamical equilibrium predicted its value before Gamow and with better accuracy. And not only this, Max Born also predicted that the cosmological redshift and the cosmic background radiation should be related with radio astronomy eleven years before the discovery of the CBR by Penzias and Wilson utilizing a horn reflector antenna built to study radio emissions!

Our conclusion is that the discovery of the CBR by Penzias and Wilson is a decisive factor in favour of a Universe in dynamical equilibrium, and against models of an expanding Universe, such as the Big Bang and the steady-state.

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Appendix

The Energy Flux of Cosmic rays

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The total quantity of energy that falls on 1 cm² per second at the edge of the atmosphere in the form of cosmic rays is equivalent to 3.53×10^{-3} *erg cm*$^{-2}$ *sec*$^{-1}$*. On the whole surface of the earth this energy would amount to 2.4 million HP. This energy flux is nearly equal to the flux which arrives in the form of light and heat from the fixed stars. We now discuss the effects of this phenomenon on the temperature of interstellar space.*

I have recently published the intensity curve of cosmic rays, measured with an electrometer-recorder at different altitudes of the atmosphere, up to a minimum air pressure of 22.2 mm Hg[*] [†]. The observed intensity pattern was of such nature that it was easy to extrapolate the limit value J_∞ of the cosmic rays when it enters into the atmosphere. The value given earlier has been improved in the meantime, determining experimentally the factor which reduces to 1 atm. the measurement of the intensity in an ionization chamber containing air at about 5 atm. In the first publication, this factor was simply assumed to be proportional to pressure, but in this way we naturally obtained only a first approximation. We now have an increase of the indicated ionization values of about 20%, and for J_∞ we obtain a result which corresponds to the energy necessary to form 333 ion pairs per cm³ per second in air under normal conditions.

If we represent the intensity of cosmic rays of the ion pairs produced as a function of the altitude which refers to a homogenous atmosphere (with a constant density $r_{0.760}$), the graphical integration of the resulting curve shows the number of ions which are produced by cosmic rays if it is completely absorbed in a sufficiently high column of air with a cross section of 1 cm². We obtain a very high number of 6.93×10^7 ion pairs per second. Millikan and Cameron[‡] have made this calculation before, but due to insufficient experimental documentation they obtained a result of only 1.28×10^7 ion pairs.

If we assume that for the production of one ion pair[§] in the air we need an energy of 32 eV, we obtain an energy flux due to cosmic rays of $S_U = 3.53\times10^{-3}$ erg cm^{-2} sec^{-1} at the earth. The energy of an alpha particle at a velocity of 2×10^9 cm/sec. is 1.5×10^{-5} erg. The energy flux per cm² produced by cosmic rays is thus as great as that produced by several hundred alpha-particles per cm² per second.

It is quite remarkable that the energy flux produced by cosmic rays is nearly equal to the energy received per cm² per second on the earth from all the fixed stars. Millikan and Cameron had earlier indicated[**] the quantity of this energy as 3.02×10^{-3} erg cm^{-2} sec^{-1}, as the total quantity of light emitted by the fixed stars was given as equal to the quantity of light emitted by 1,092 first magnitude stars, with the brightness of a first magnitude star comparable to the sun and solar constants. The total brightness of all fixed stars is naturally only an approximately known value, which, moreover, varies according to the brightness it is referred to: visual, photographic or bolometric brightness. Van Rhijn[††], for example, indicates the directly measured visual brightness of the sky as equal to 1,440 stars of the first visual magnitude according to the Harvard scale or 1,560 first magnitude stars according to the international scale. Based on these parameters, it is possible to estimate the energy flux of fixed stars at about 3 to 5 (or somewhat more) $\times10^{-3}$ erg cm^{-2} sec^{-1}. Eddington[‡‡] even indicates a value of 5.75×10^{-3} erg cm^{-2} sec^{-1}. The value for the flux density of the energy produced by cosmic rays is 3.53×10^{-3} erg cm^{-2} sec^{-1} and comes up very close to the above results. This value might even be more certain than the value indicated for the radiation emitted by the fixed stars, but it will be soon better known after several measurements in the stratosphere. A measurement of cosmic rays in the ionization chamber can be made quite precisely once the initial difficulties have been overcome. The value used for ionization is obtained with the slower electrons and then applied to the very fast secondary electrons in the cosmic rays, but the uncertainty of the result due to this fact should not be very great.

On the whole surface of the earth, there is an energy flux of 1.8×10^{16} erg per second, or 2.4 million HP. Compared to the sun, neither this energy nor the total quantity of light emitted by the fixed stars are of any importance for the earth. However, the density of energy produced by cosmic rays, which is nearly equal to the density of light and heat emitted by the fixed stars, is very interesting from an astrophysical point of view. A celestial body with the necessary dimensions to absorb the cosmic rays—in case of a density of 1, a body with a diameter of several meters (5 meters of water absorb $\frac{9}{10}$ of the cosmic rays)—will be heated by cosmic rays. The increase in temperature will be proportional to the energy of absorbed cosmic rays (S_U) and the surface (O). The temperature of the body will increase until the heat it emits—in case of black body radiation $s \cdot T^4 \cdot O$—reaches the same value. We then obtain a final temperature of $T = \sqrt[4]{S_U/s}$. Substituting numerical values we obtain 2.8 K.

[*] E. Regener. *Die Naturwissenschaft* 20:695, 1932.

[†] Note added in proof: An ascent on 3rd January 1933 reached an altitude of 22 km and yielded the same result as the previous flights.

[‡] R.A. Millikan and G.H. Cameron, *Phys. Rev*. 31:930, 1928.

[§] H. Kulenkampff, *Physikalische Zeitschrift* 30:777, 1929.

[**] R.A. Millikan and G.H. Cameron, *l.c.*

[††] P.J. Van Rhijn, *Groningen Publ*. N.31, 1921.

[‡‡] A.S. Eddington, *Der innere Aufbau der Sterne*, 1928, page 469. Here the energy density of radiation is given in erg cm^{-3}.

Naturally, the density of the cosmic rays depends on where it was formed. Since we hardly know anything certain about it at present, we can only discuss different possibilities. At some point in our local system of fixed stars which is not near the sun or other fixed stars, the normal light and heat emitted by a fixed star heats a blackbody to 3.16° absolute, if, following Eddington (*l.c.*), we suppose radiation of 5.75×10^{-3} erg cm^{-2} sec^{-1}. If we now add the cosmic rays, together with the radiation emitted by fixed stars, it would increase the temperature of a blackbody (according to the T^4-law) to 3.56 K only, on the condition that the cosmic rays is created in our local star system and the density where it is created is the same as on the earth. The effect in intergalactic space between the nebulae is quite different; here the visual brightness of the sky would be very low, since only the weak light of the nebulae is present and our own Milky Way system with all its fixed stars would appear as another nebula. The space thus defined would correspond approximately to the whole universe known to us. If cosmic rays were created in such a space, its temperature determined by the density of radiation, would depend above all on the cosmic rays, because the normal density of radiation is very low and the density of cosmic rays would hardly be lower than on the earth. In the nebulae (galaxies) the temperature of the space would, moreover, be increased by heat radiation, and only near some fixed stars would the temperature depend exclusively on heat radiation.

The Radiation Temperature of the Universe

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1. The question as to the temperature in the universe never raised any particular problems in the past because, supposing that the universe was subject to a continuous process, it was impossible to indicate any specific temperature. The greater we estimate the age of the nebulae, the more radiation the space between them must contain.

Things were quite different as regards the temperature of the intergalactic space; even if some stars shine only some thousand million years, this is quite enough time to establish a certain radiation temperature; this temperature is clearly defined by the luminosity, the number, and the distribution of stars. According to a study carried out by E. Regener[*], a blackbody, which is not situated near the sun or near another fixed star would heat up to 3,16°, though there is an uncertainty of at least 0.5° surrounding this value. A small particle of carbon would therefore heat up to this temperature in interstellar space; a block of carbon of a diameter of several meters however, would reach a higher temperature because of the cosmic rays (Regener indicated a value of 3.6° for this case, but in a kind letter he indicated informed that we have only vague information about the energy density of cosmic rays in space).

If we adopt my hypothesis of a stationary universe[†] (a hypothesis which I have used successfully to draw several conclusions) we must assume that the space between the nebulae contains a constant, well-defined quantity of radiation. This idea led me to formulate the equation for the red shift as function of time, which occurs quite clearly in distant celestial bodies, *i.e.*

$$-\frac{\mathrm{d}(h\nu)}{\mathrm{d}t} = H \cdot (h\nu) \qquad (1)$$

an equation which should be open to considerable generalization (see #1 page 639 *ff.*). Accordingly, we can now make the following assumptions about the temperature in the space: the nebulae are shining continuously; whereas we are able to indicate an approximate age for the fixed stars (#1 page 637), we must suppose that nebulae are much older or even infinitely old; despite all this, we have in the intergalactic space a well-defined temperature: on one hand, numerous and regularly distributed stars emit a constant radiation, but due to the energy reduction corresponding to the red shift the temperature of the space is maintained at a certain maximum level, and it is obviously possible to calculate this value in a rather simple and concrete way, in spite of the obvious complexity of the problem.

As far as Hubble's ideas (see #1 page 635) are concerned, I would like to stress, with regard to erroneous considerations, that we naturally do not have values for the colour index, the luminosity, the mass as well as the average distance between nebulae which correspond exactly in every case. Instead, we are confronted with wide statistical fluctuations superimposed upon one another, in keeping with my hypothesis, but it should not be impossible to calculate the average value. For approximate calculations we can consider—as already shown successfully by Hubble[‡]—that the results correspond to the above data for nebulae, and thus we may follow the same procedure in dealing with the present problem.

2. A rather complicated calculation would be needed in order to find the increase in temperature of carbon particles at a point very far away from a nebula by summing the radiation from all nebulae (including the ones infinitely far away), and in this case we would naturally have to consider the influence of the red shift, *i.e.* the loss of energy of each light quantum which reaches that point (by applying equation (1)[§]). Instead, we proceed on the following assumptions: if we move from one nebula to the next, the temperature will at first be high, then decrease, and then increase again as we approach the next nebula. Obviously, the minimum value between both extremes exhibits a pronounced leveling off because of the radiation from other nebulae, but however small this minimum value may be, it must exist. The geometrical point of the minimum value which we obtain moving from one particular nebula to all the others is, roughly speaking[**], a spherical surface within which the

[*] E. Regener, *Zeitschrift fur Physik*, 80:666, 1931.

[†] See W. Nernst, "Weitere Prüfung der Annahme eines stationären Zustandes im Weltall", *Zeitschrift für Physik*, 106:633, 1937; hereinafter referred to as #1.

[‡] See the interesting publication by E. Hubble, *The Realm of Nebulae*, New Haven, USA. (1936).

[§] Without equation (1) the result would not be correct; see #1 page 644.

[**] The same quantity of light enters and comes out through every element on the surface of such a delimited space, we can also imagine it enclosed within a perfect mirror, considering it totally isolated from the rest of the world.

nebula in question is enclosed and obviously the volume of the space thus defined is equal to the average volume of each nebula.

Since, according to Hubble, the average distance between two nebulae is of about 2 million light years, the space V controlled by each nebula, and which I called some time ago (#1 page 649) the nebula's "sphere of action", is 8×10^{72} cm^3. Let us suppose—and the following demonstrations rather confirm this hypothesis—that the radiation emitted by the nebula (which is $E = 1.03 \times 10^{49}$ erg per year)* will fill up the above volume until it contains the nearly constant energy of e erg/cm^3, then from equation (1) we have:

$$E = (eV)H$$
$$e = \frac{1.03 \times 10^{40} \times 1.84 \times 10^{9}}{8 \times 10^{72}} = 2.36 \times 10^{-15} \ \ \text{erg / cm}^3, \qquad (2)$$

where E represents the energy which is dissipated each year by the red-shift; 1.84×10^{9} is the value, expressed in years, of $1/H$ in equation (1) and eV is the radiation energy contained in the "sphere of action".

In order to obtain the temperature of the space, we use the familiar formula for energy per cm^3:

$$2.36 \times 10^{-15} = \frac{4sT^4}{c}$$

which yields

$$T = 0.75°$$

In intergalactic space (see above) we had T = 3.16°, hence much higher—close to four times as high. According to the Stefan-Boltzmann Law, the energy contained in the radiation is then approximately 4^4, *i.e.*, 256 times as high. Our value, which we cannot prove in another way at present, is therefore quite plausible. In this case too, as in many other calculations carried out according to my theory with quite high decimal powers, we obtain a quite reasonable result, and this may be another hint that my considerations may not be falsified by complications unknown at present. To be sure, this possibility must always be kept in mind, because phenomena so far unknown to us can influence astrophysical observations at any time.

The "Universe temperature" calculated above refers to the space between the nebulae; it is naturally higher near a nebula. In this case we must apply

$$T^4 = \frac{3.27 \times 10^{11}}{4pr^2 \times 5.7 \times 10^{-5}},$$

where the numerator represents the radiation of the nebula in erg per second. If the distance r is 2.0×10^{4} light years, the temperature is 0.7°; since half the distance between the nebulae is 10^6 light years, it follows that the space in which the temperature increases due to the presence of a nebula is very small compared to V (the "sphere of action"), and we were thus right to calculate as if the temperature between the nebulae was more or less constant nearly everywhere.

3. We were able to calculate the temperature of Universal space with equation (1), which is also interesting from a purely physical point of view. The above considerations represent another instance of the logical power of this equation. The old hypothesis, which as we know, perplexed Hubble based on his astronomical measurements, interpreted the strong red shift of distant radiating objects, as well as those located close by, as a Doppler effect. The conclusion that the red-shift of the nebulae was proportional to their distances led to the strange consequence of an "exploding Universe", as summarized in the following two equations ($l - l_o$ = red shift in wavelengths):

$$\text{(a)}\ \frac{v}{c} = \frac{l - l_o}{l_o}, \qquad \text{(b)}\ Hr = \frac{l - l_o}{l_o}.$$

Now, no physical objection can be raised against the first equation (Doppler effect); the second, according to which the red shift—*i.e.* according to (a) also the velocity with which the nebulae move away from our Milky Way system—is in proportion to the distance r† between the nebulae and the earth, implies a rather strange requirement and even makes equation (a) somewhat illusory.

Independently of the above, our new equation (1), however, gives a clear and consistent interpretation of the astronomical measurements; the red shift, for example, is proportional to the distance of the nebulae simply because if the distance is twice as great, the light-beam needs twice the time to cover the distance between the nebula and the observer on earth. Moreover, equation (1) does not constitute an *ad hoc* hypothesis, as is the case for equation (b). In fact, as early as 1921, I predicted implicitly the existence of red shift (see also #1 page 639), based on my new conception.

Moreover, equation (1) on one hand, and the equations (a) and (b) on the other, lead to the same results only if

$$\frac{l - l_o}{l_o} = \frac{n_o - n}{n}$$

is much less than 1. In the astronomical measurements made to date, this condition is generally met. However, if it is possible to carry out measurements with greater precision, it may soon be possible to decide between the values $n_o - n/n$ and $\ln(n_o/n)$ experimentally, and this would be a further contribution to the very fundamental and currently so often discussed question whether the red shift is a Doppler effect or not.

4. In addition to the radiation emitted by nebulae, space is also filled with cosmic rays, the energy density of which is much higher, according to Regener (*l.c.*). We may regard the two types of radiation as coexisting, just as Regener does. Yet, according to thermodynamics (and as pointed out by my colleague von Laue), the cosmic rays should transform into normal blackbody radiation, though this transformation is probably such a slow process (I do not wish to enter into details now) that its rate is very low compared to the rate of transformation via red-shift required in equation (1)‡.

Furthermore, the above calculated energy density of the radiation emitted by the nebulae is not constant, because this radiation is not a blackbody radiation in the sense of the 0.75 K temperature, but it is similar to the radiation emitted by the sun. In any case, we may suppose that this radiation will continue to exist unaltered in space, for the same reasons as the cosmic rays, despite the "galactic" dust which is present everywhere§, which should really act as a catalyst. Moreover, the transformation processes just discussed have at present only secondary importance for astrophysics.

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* The sun emits yearly 1.17×10^{41} erg. With Hubble we suppose that the average luminosity of a nebula is of 88×10^{6} solar magnitudes, and thus obtain the above value.

† It is helpful to indicate this distance in light years; in this way we also know the time of flight expressed in years, a value we need for equation (1). Despite the different dimensions, H is assigned the same numerical value in both equations (1) and (a).

‡ See #1 page 656.

§ Present in very minute quantities in the space between nebulae!