А. В. Бялко

Наша планета — Земля

Издательство «Наука», Москва

A. V. Byalko

Our Planet — the Earth

ИЗДАТЕЛЬСТВО МИР

Mir
Publishers
Moscow

Translated from Russian by Yu. M. Taube
Russian edition edited by Ya. A. Smorodinsky
First published 1987
Revised from the 1983 Russian edition

To the Reader

Mir Publishers would be grateful for your comments on the content, translation and design of this book. We would also be pleased to receive any other suggestions you may wish to make.

Our address is:
Mir Publishers
2 Pervy Rizhsky Pereulok
I-110, GSP, Moscow, 129820
USSR

На английском языке

Printed in the Union of Soviet Socialist Republics

Contents

Introduction

We live as in a mystery dream
On one of convenient planets...

The Russian poet Igor Severyanin wrote the above lines in 1909. His idea of a mystery dream implied, I believe, not the lack of scientific explanation of the convenience of our planet. But poet's intuition carried the spirit of his times into his work. This makes readers see more between the lines than the poet himself intended to say. Our understanding of physical phenomena occurring on the Earth has so advanced since, that the state we are in can be no longer called a dream. It is rather the state soon after awakening: logical associations are already established but the consciousness is not yet completely clear.

There is, however, a set of phenomena occurring on the Earth or in the solar system where the cause and effect relationships are quite clear. This book deals with relations and integrity of astronomical and climatic phenomena. These relations are based on celestial mechanics and thermal equilibrium of planets in general and their external containments, atmospheres, for one. The distinguished Soviet geophysicist A. S. Monin introduced the term "geonomy" for the science which deals with a comprehensive analysis of the Earth and its cosmic fellows. Yet this book is no *Geonomy Made Easy* since it does not describe magnetic fields of the planets, as well as electric and optic phenomena in the atmospheres.

We shall make an armchair tour round the Earth and its cosmic surroundings. Our vehicle in this tour will be the knowledge of the basic laws of nature. Theory will guide us to such places which are impossible to be reached even by spacecraft. For example, we shall visit the center of the Sun. However, the description of nature is not our major objective. There are, naturally, some descriptions in this book but they only serve to illustrate the explanations of phenomena. Our wish has been to explain the structure of the world and to demonstrate what makes it so "convenient" to live in.

We begin with pinpointing the exact location of our great home in space and time, namely, describe the part of the universe immediately around us, and the motion of the Earth around the Sun. In Chapter 1 we introduce certain physical notions which are quite complicated compared to those studied at school but which we need for the discussion which follows.

Chapter 2 describes the Earth and planets not as material points but as rotating bodies conforming, however, to forces acting between them. Chapter 3 is focused completely on the Sun, the principal source of energy and the center of attraction in the solar system. Chapter 4 deal with the effect of the solar radiation and chemic composition on the structure of the atmosph and oceans, with the origin of winds and oce currents. Finally, Chapter 5 analyzes the caus of climatic changes on our planet. Amazing climatic alterations over long time intervals depend also on the motion of other planets. So this is the scope of problems discussed in this book.

Chapter 1

The Earth's Path in Space and Time

1. Celestial Sphere

Look at the sky illuminated by countless stars at a clear night. You know that the distance to them is enormous in terms of terrestrial thinking. You already know quite a lot about the arrangement of our world but leave aside the book-knowledge and try to feel the Earth, a tiny grit of the universe rotating and moving in space. Difficult, isn't it? Try again after having read this book.

In this book we treat the Earth in its interaction with the surrounding part of the universe. Therefore we must first of all identify our exact location in space. The celestial sphere, or simply stars in the sky, are our initial frame of reference by which we find direction in space. The variety of stars is very rich. Some of them shine, others are hardly visible. The colour of light may vary from blue to yellow and shades of red. Stars are distributed over the sky quite unevenly: there are some locations where stars are scarce and then comes the Milky Way, a luminous band across the night sky composed of stars which cannot be separately distinguished by a naked eye. The ancient Greeks had a similar name for the Galaxy: Kyklos Galaktos, the milky ring.

If you keep looking at the sky for a long time or memorize the locations of stars and then have

another look at them, you may easily note that the stars have changed positions. This change is however universal: the whole world of stars rotates around us. Of course you know that it is, in fact, the Earth which rotates in relation to stars.

To simplify the orientation in space we should rather disregard the Earth's rotation.

Imagine that you are a cosmonaut observing stars from the orbit of a satellite. It takes you half a turn, less than an hour, to get the view of the entire universe. The dispersed atmospheric light does not interfere and the stars can be seen even near the Sun. Stars do not twinkle in space, the twinkling being the effect of air motion in the Earth's atmosphere. And, what is most important, in space we may disregard the geographical latitude, the time of the day, and the season of the year since the location of stars on the celestial sphere is practically permanent.

Ancient humans observed almost the same view of the celestial sphere: the relative displacement of stars over several thousand years is insignificant, therefore constellations have retained their shapes. The names of many constellations stem from ancient times. Strictly speaking, constellations are 88 arbitrary configurations of the celestial sphere, the boundaries between which were established by the International Astronomical Union between 1922 and 1930. The history of constellations goes back to the groups of stars visible by a naked eye and the ancient names of constellations may stem from the configurations produced imaginarily by linking stars with lines. Drawings of ancient astro-

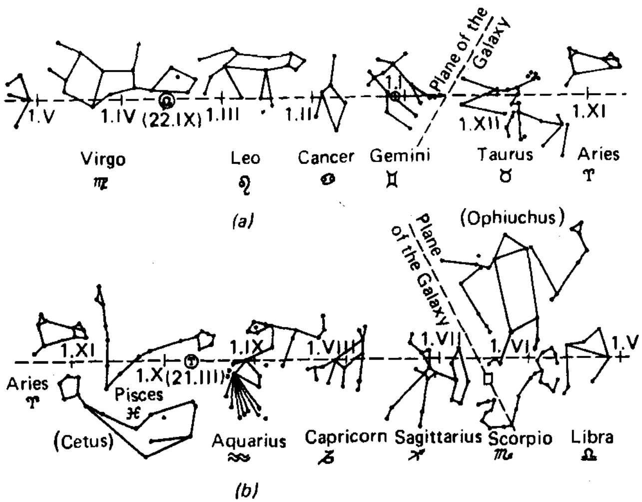


Fig. 1. (*a*) Diagram of Zodiac constellations. The horizontal dashed line is the ecliptic. The point of vernal equinox ♎ and the direction to the Earth's perihelion ⊕ are indicated on the line.
(*b*) Diagram of Zodiac constellations (continued). ♈ is the point of vernal equinox, □ indicates the direction to the center of the Galaxy.

nomers have not survived to our times. Figures 1 and 2 give the shapes of constellations suggested recently by the American astronomer G. Ray. Yet a look at his sketches of Leo and Aquarius makes us think that he has only reproduced ancient drawings by those who had named the constellations. The names have come to us from ancient Greeks, but the Greeks had borrowed the division of the celestial sphere into constellations from the ancient Babylonians. No-

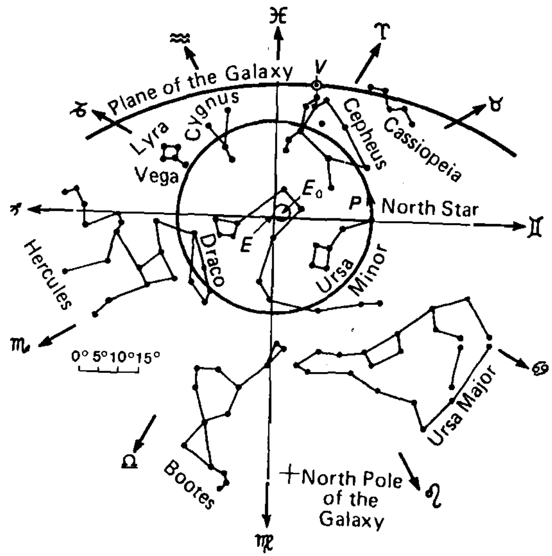


Fig. 2. Diagram of constellations of the northern hemisphere. *P* is the direction to the celestial pole, the larger circle is its trajectory; *E* indicates the pole of ecliptic, the smaller circle is its trajectory; E_0 is the direction of the solar system's momentum; *V* is the direction of the solar system's velocity in the Galaxy; + indicates the north pole of the Galaxy.

tably, in ancient China stars were grouped into constellations absolutely differently.

In Fig. 1 twelve constellations are located along the dotted line to form the Signs of Zodiac: Aries (♈), Taurus (♉), Gemini (♊), Cancer (♋), Leo (♌), Virgo (♍), Libra (♎), Scorpio (♏), Sagittarius (♐), Capricorn (♑), Aquarius

(♒), and Pisces (♓). In brackets there are symbols invented in ancient times to designate these constellations. "Zodiac" is a Greek word meaning "animal" although the Signs of Zodiac include not only animal names.

Figures 1*a* and 1*b* are the developments of a part of the celestial sphere. The dashed line represents the great circle of the celestial sphere. The drawing is closed while in fact the Zodiac constellations are cyclic: Pisces are followed again by Aries. This great circle of the celestial sphere is called ecliptic. The ecliptic is the path of the Sun among the stars during a year as observed from the Earth. Stars cannot be distinguished at day time because of the solar light dispersed in the atmosphere. Yet even the ancient Babylonians understood that stars do not disappear at day and could determine Sun's location in relation to constellations at any given moment of time.

Figure 1 gives not only Zodiac constellations but also two other ones: Ophiuchus and Cetus. Ophiuchus, the Serpent Bearer, is positioned on the ecliptic but it was not included into Zodiac probably on the grounds of its ugly appearance and because of a superstitious wish to make the number of Zodiac constellations "luckier". We have added Cetus because Ray had made it look so attractive and partly also on the grounds of superstition.

For orientation we shall need constellations of the northern hemisphere given in Fig. 2. The center of this figure, point E, is positioned in relation to the ecliptic just as the North pole of the Earth in relation to the equator, while

directions to Zodiac constellations are indicated by arrows. Note that the North Star is not in the center of the figure but near point P.

Astronomers can calculate distances to stars. In fact, stars which compose a constellation are rarely close to one another. In most cases the "neighbouring" stars are separated by enormous distances and their neighbourhood is purely optical.

The same is true for distances from this planet to stars. Thus Vega of Lyra constellation is located at the distance of 2.5×10^{17} m which is 1.5 million times more than that to the Sun. Vega's light reaches our planet in 26.5 years. Such great distances account for the fact that the positions of the stars in constellations are practically constant. In fact, stars travel in relation to one another with measurable velocities. The average velocity of a star is 100 km/s. The figure seems impressive, but let us calculate the time taken by a star moving at such a speed perpendicularly to the direction from us to the star (which is located very close to us, e.g. like Vega) to transit by 1 degree in relation to other, distant, stars. This time is:

$$t = \frac{1^\circ}{180^\circ}\pi\frac{2.5\times10^{17}\ \text{m}}{10^5\ \text{m/s}} \simeq 4\times10^{10}\ \text{s} \simeq 1400\ \text{years}.$$

There are however stars which transit over the celestial sphere faster than by 1 degree in 1.5 thousand years but such stars are very few. Most stars change their locations much slower since they are situated farther than Vega. For this reason the layout of constellations was practically the same in ancient times as it is today. It should be noted, however, that the general view may change not only due to the displacement of stars but also because of the alterations in star luminous emittance. It is known, for instance, that Betelgeuse which is presently a red star was mentioned in ancient Chinese chronicles as a yellow star. The general view of a constellation may change radically if only one star turns invisible. This may account for the fact that the ancient names of constellations look strange to the modern eye. Unfortunately, it is yet impossible to calculate the evolution of numerous stars back to ancient times with sufficient accuracy as well as to estimate their luminous emittance at that time.

As mentioned above, stars concentrate on the celestial sphere about the Galaxy. Through a sufficiently powerful telescope one can see that the Galaxy itself is composed of individual stars. However, the projections of these stars on the sphere are so close to one another that a naked eye can distinguish nothing but a continuous luminous cloud. If observed from the Earth, the Galaxy seems to stretch all the way across the sky from horizon to horizon, but for a cosmonaut who can see the entire heaven it is a band of stars around us. The ancient Greeks somehow guessed it: they were the only people to call the Galaxy a circle (Kyklos Galaktos).

Nowadays we use the word "Galaxy" to denote the system of stars housing our Sun and the Earth. We mean thereby not a circle in the celestial sphere but a real three-dimensional formation of stars. We study the Galaxy from the inside but if a sketch of it were made by an outside observer, the resulting picture would have rather an odd shape. The Galaxy looks like a flat and round pancake with a bulge in its center. Spiral "sleeves" extend from the center of the galactic plane and the concentration of stars there is relatively higher. The Galaxy does not have clear boundaries.

The maximum concentration of stars is in the center of the Galaxy, in its nucleus. Unfortunately, the investigation into the nucleus is hindered by interstellar matter which absorbs light. At that place—between Sagittarius and Scorpio—the Milky Way seems to fork over leaving a dark band in the middle. From the center of the Galaxy we receive radio-frequency radiation and short-wave X-radiation; the structure of the galactic nucleus was also studied in infrared light.

Figures 1 and 2 give the galactic plane, the direction to the center of the Galaxy, and the galactic North pole. Sun's place in the Galaxy is near the center of the galactic disk. If it were otherwise the Milky Way would not look like a band around the great circle of the celestial sphere but would seem just a bright spot covering an extensive area. The distance from the Sun to the center of the Galaxy is about $a_{\odot} \simeq 3 \times 10^{20}$ m which by two billion times exceeds that from the Earth to the Sun: $a_{\oplus} = 1.5 \times 10^{11}$ m.

Stars of the Galaxy rotate around its nucleus in conformity with the law of gravitation. The projection of the galactic velocity vector of the Sun is indicated by point V in Fig. 2. The vector lies in the galactic plane, and this means that the Sun has always been in the galactic plane.

The orbital velocity of the solar system $V_{\odot} \simeq$ 250 km/s. The period of the system's revolution around the galactic center can be assessed as $2\pi a_{\odot}/v_{\odot} \simeq 7 \times 10^{15}$ s, i.e. more than two hundred million years.

The law of gravitation permits to calculate the galactic mass inside the Sun's orbit. The total galactic mass approaches this estimation by the order of magnitude:

$$m_g \sim \frac{v_{\odot}^2 a_{\odot}}{G} \sim 3 \times 10^{41} \text{ kg},$$

where G is the gravitational constant equal to 6.67×10^{-11} $m^3/(kg \times s^2)$. The total mass of the Galaxy exceeds that of the Sun by a factor of 10^{11}. Approximately this number of stars makes up the Galaxy.

2. The Cosmological Time Scale

The farther from us a cosmic body, the weaker, certainly, its action. However, the weakness of a given action compared to another one is not a sufficient reason to neglect minor disturbances completely. Let us exemplify it.

The greatest force acting upon the Earth is the gravitation of the Sun. Compared to that force, the force of attraction to the center of the Galaxy is insignificant:

$$(a_{\oplus}/a_{\odot})^2 m_g/m_{\odot} \sim 3 \times 10^{-11}.$$

Is it negligible? The answer depends upon the period of time during which the motion is considered. If it is a period of several years, i.e. several turns of the Earth around the Sun, the

effect of galactic gravitation is quite negligible. But if the period in question covers hundreds million years, which is comparable to the period of revolution round the galactic orbit, it is just the weak but constant force of galactic attraction that becomes the major force dictating the Earth's trajectory. The solar gravitation causes only minor alterations of the Earth's trajectory near the galactic orbit of the Sun. Note that the velocity of galactic motion is almost ten times greater than that of the Earth around the Sun.

To study cosmic effects on our planet we may certainly limit ourselves to the Earth's motion in the solar system and the Sun's motion in the Galaxy. But the time scale we shall need for that purpose is larger than the period of revolution round the galactic orbit. Thus we shall focus on the longest time periods, i.e. cosmological time. To do so we shall have first to go back to the description of the surrounding space outside the Galaxy.

There is a great number of equally enormous star systems beside the Galaxy, some of them are similar to ours, others differ significantly. They are called galaxies (with small letter). The nearest two galaxies are Magellanic Clouds observable from the Earth's southern hemisphere. They are removed from us at the distance of 1.6×10^{21} m; the size of each galaxy is about 2×10^{20} m. The Magellanic Clouds are irregular in form and their mass is much less than that of the Galaxy. They are gravitationally connected, i.e. they are Galaxy's satellites.

High-power telescopes permit us to see an enormous number of galaxies, about 10^{11}, removed to immense distances reaching 10^{26} m. Galaxies are distributed over space quite unevenly, the majority of them being joined into clusters of galaxies. Clusters, in turn, tend to join into superclusters. Nevertheless the universe in general seems to be filled with matter rather evenly; even the number of superclusters in the observable part of the universe is quite significant.

In the early 30s the American astronomer E. Hubble proved by observations that velocities of remote galaxies are directed from us. Moreover, the farther a galaxy, the faster it escapes. The galactic velocities are proportional to the distance to the respective galaxies (this statement is called the Hubble principle). The actual proportionality factor is hard to establish: the universe distances are too long compared to terrestrial measures. The value of the Hubble constant H is about 50-100 km s^{-1}/megaparsec. It demonstrates the rate of recession per megaparsec. The parsec, an astronomical unit of length, eguals the distance at which a base line of one astronomical unit subtends an angle of one second of arc. Thus, it is easy to calculate: megaparsec is equal to $3{,}086 \times 10^{22}$ m. Let us transfer the Hubble constant from astronomical units to the physical with decreased dimensions of length. Then H is approximately 3×10^{-18} s^{-1}.

The idea of the expanding universe implies that all matter of the world was initially packed into a compact superdense agglomeration and then it was hurled in all directions by a cataclysmic explosion. The higher the initial velocity of matter, the farther it has recessed. The fartthest of discovered galaxies move at a speed comparable

with the velocity of light. We shall see further that there is no complete analogy between a conventional explosion and the big-bang expansion of the universe. Yet a natural question may arise: how much time has elapsed since the Big Bang?

To answer this question one must know—beside the Hubble principle—how the universe gravitation decelerates the expansion. This and other problems concerning our world in general are the subject of cosmology. It is quite easy to make an approximate assessment of the age of the universe if gravitation is neglected. Taken the velocities of galactic recession time-independent, we get:

$$t_0 \sim H^{-1} \sim 3 \times 10^{17} \text{ s} \sim 10^{10} \text{ years.}$$

More accurate calculations indicate that the age of the universe is between 14 and 20 billion years. The time counted from the start of expansion is called cosmological time.

Amazingly, the extraordinary idea of the expanding world had been theoretically predicted before it was proved by observations. In 1922 the Soviet scientist A. A. Fridman demonstrated that most solutions to Einstein's equations for the world as a whole are unstable and depend on time, and that the expansion of the universe is the most natural effect of gravitational equations. Fridman lived a short life (1888 to 1925) but he carried out a number of most interesting mathematical research and investigations into the theory of the Earth's atmosphere. The final statement of Fridman's work *On the Curvature of Space* (published before the galactic expansion was discovered and the Hubble constant was first calculated) was the following: "Taken M to be equal to 5×10^{21} masses of the Sun, we get the age of the world to be equal to about 10 billion years." M represents here the mass of the observable universe. Science knows very few examples of such a deep insight!

A clock able of measuring time periods of billion years is also available. For this purpose the radioisotope technique is employed. The technique is based on the instability of isotopes of some chemical elements. Isotopes decay spontaneously and transmute from one to another. The number of radioactive atoms and the mass of the isotope decrease with time in all cases independently of external conditions and in conformity with the following principle:

$$m(t) = m(0)\, 2^{-t/T_{0.5}},$$

where $m(0)$ is the initial mass of the isotope, and $T_{0.5}$ is the half-life, a constant value strictly individual for each isotope. The half-life is the time in which the amount of a radioactive nuclide decays to half its original value.

Half-lives of various isotopes are absolutely different. Short-living atomic nuclei decay in millionth fractions of a second; there are isotopes with $T_{0.5}$ equal to several seconds, the half-life of others may be minutes, days, years. We know presently more than two thousand isotopes of the 107 elements of the periodic table. 305 of them are stable or have half-lives by far exceeding the age of the universe. The distribution of half-lives of other isotopes is given in Fig. 3. It demonstrates that the major part of

unstable isotopes has specific lives between a minute and a week, but there are also some long-livers. The latter are used for radioactive dating.

Nuclear reactions which take place in the cores of stars generate various isotopes of chemical

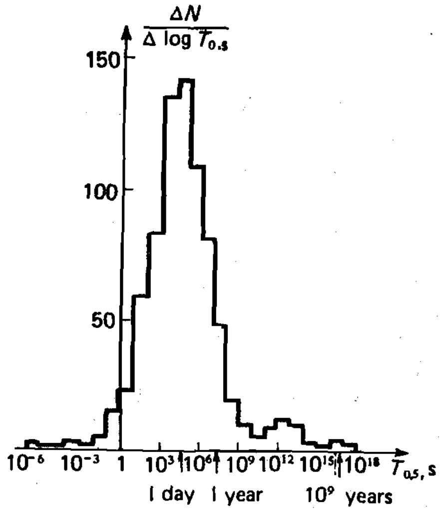


Fig. 3. The distribution of half-lives of isotopes.

elements. We shall discuss some of these processes taking as an example our star, the Sun. There is one more source of unstable isotopes, namely nuclear reactions in the upper layers of the atmosphere induced by fast particles of cosmic rays. That is how Earth's atmosphere, for example, is enriched with carbonic acid which contains carbon isotope ^{14}C. The isotope's half-life is 5570 years. Measuring the content of ^{14}C in wood, one can calculate the time when that tree was green and growing, when it synthesized organic compounds from the atmospheric carbon dioxide.

Isotopes of star origin with half-lives between 10^5 and 10^7 years have not survived in the Earth's crust. Such isotopes appeared on Earth only after 1942 as a result of controlled nuclear reactions and nuclear explosions.

Finally, several isotopes have half-lives comparable to the age of the universe. These include two uranium isotopes, ^{235}U and ^{238}U, thorium ^{232}Th, potassium ^{40}K, and strontium ^{87}Sr.

A comparison of concentration of these long-livers with the concentration of those they turn into allows to determine the age of oldest rocks, i.e. the time which has passed since the moment of their last melting. For example, out of potassium ^{40}K, which is a component of solid minerals, a gas is slowly formed, argon ^{40}Ar. It is assumed that all argon admixtures have left the sample of rock during the last melting and all argon atoms newly formed from potassium cannot break through the crystal lattice of the solid. Thus the number of argon atoms will be equal to that of the remaining ^{40}K in a rock aged, for instance, 1.26×10^9 years which is the half-life of ^{40}K.

Rocks aged between 10^5 and 10^7 years are dated by way of track counting, i.e. counting the traces of fast particles produced by decay process. The most convenient material for this measurement technique are glassy particles of volcanic tuff and ash. Amazingly, the greatest relative error occurs in dating of rather young rocks aged between 30 and 100 thousand years. These rocks are too young for track techniques, not to mention that volcanic ash falls too rarely over large areas and its concentration is insufficient for an accurate dating by carbon ^{14}C.

The most ancient rocks discovered on Earth are 3.8 billion years old. The age of lunar rocks and meteorites also has a limit: there is no material older than 4.6 billion years in the surrounding part of the solar system. Thus the solar system is believed to have been formed about five billion years ago.

Notably, the age of the solar system determined by the radioisotope technique does not contradict the age of the universe determined by galactic recession. It is slightly less but of the same order of magnitude.

In *The Karamazoff Brothers* by Dostoevsky, a certain Smerdyakov asked Grigory, Karamazoff's servant:

— The Maker created light on the first day and the Sun, the Moon, and stars on the fourth. But where did light shine from on the first day? For which curiosity he was beaten up.

3. Big Bang Light

Had the light shone before the galaxies and stars were formed? Yes. The Big Bang detectable by the galactic expansion had heated the matter of the universe to extremely high temperature. The temperature decreased with expansion, and radiation, which uniformly filled the entire universe, also changed. Yet this primary light still exists. Invisible to the eye, it can be registered by radiotelescopes.

Before we proceed to a deeper discussion of that primary light let us look into the principles of thermal radiation.* You have certainly noted that the more a body is heated the brighter it glows. The chaotic thermal motion of molecules and the frequency of their collisions increase with temperature. The fact is that these phenomena are also accompanied by intensification of chaotic electromagnetic field which we call natural light.

If a body's radiation interacts sufficiently long with the heated medium, it comes to the state of thermal equilibrium. Then the body's properties are determined exclusively by the temperature of its environment. This radiation is called the black-body radiation. Why black? The matter is that thermal equilibrium is achieved if the body absorbs the incident light sufficiently well while the absorbed energy is compensated by the thermal radiation. Bodies which almost completely absorb light of the visible spectrum look black.

Ludwig Boltzmann, a distinguished Austrian physicist of the last century, has established the principle of the thermal radiation: the density of the flux of luminous energy emitted by an absolutely black body is proportional to the fourth power of the temperature:

$$S = \sigma T^4.$$

Flux density S, which is also called radiant intensity, is the energy emitted by a unit of

* You can read about the physics of thermal radiation in more details in the book *Temperature* by Ya. A. Smorodinsky, Mir Publishers, 1984.

body's surface per unit time. Thus, the factor of proportionality σ (the Stefan-Boltzmann constant) is expressed by $J/(m^2 \cdot K^4)$. In 1900 Max Planck, the German physicist, proved the quantum nature of thermal radiation. This allowed us to express the Stefan-Boltzmann constant in terms of fundamental constants: the velocity of light c, the Planck constant $\hbar = 1.054 \times 10^{-34}$ kg·m²/s, and the Boltzmann constant $k = 1.38 \times 10^{-23}$ J/K:

$$\sigma = \frac{\pi^2}{60} \times \frac{k^4}{\hbar^3 c^2} = 5.67 \times 10^{-8}\ \mathrm{kg/(s^3 \cdot K^4)}.$$

Max Planck was occupied with the explanation of the spectrum of thermal radiation. A spectrum is a distribution of luminous intensity over frequencies. It is a function of light frequency ω related to the wavelength $\lambda = 2\pi c/\omega$ demonstrating which part of the energy falls on the frequency range $d\omega$*. Planck was the first to introduce the notion of light quantum, the photon, and employ this new physical idea to explain theoretically the observable spectra of an absolutely black body:

$$\frac{dS}{d\omega} = \frac{\hbar}{4\pi^2 c^2} \times \frac{\omega^3}{e^{\hbar\omega/kT} - 1}.$$

The left-hand side of the equation is the radiant intensity of frequency, ω, related to the spectral interval $d\omega$. Its dimensions are $J/(m^2 \cdot s \cdot s^{-1})$. The seconds can be easily cancelled but the di-

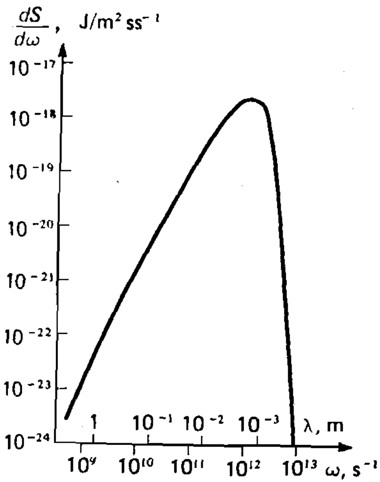
* We could write, of course, a more conventional $\Delta\omega$, the minor frequency range, instead of the differential. The differential should be understood as a small increment. The increment is so small that the variable (ω in this case) and the function do not practically change.

mensions are more characteristic of the value $\frac{dS}{d\omega}$ if written that way. The right-hand denominator includes a power of the number $e = 2.718$, the base of natural logarithms. The thermal spectrum reaches its maximum at a frequency of $\omega_m = 2.82\ kT/\hbar$. If we plot the radiation spectrum $\frac{dS}{d\omega}$ vs frequency, the area under the curve would yield exactly the value of the Boltzmann intensity σT^4. Thus, the intensity of the thermal equilibrium radiation, the frequency of the maximum of its spectrum, and the entire spectral dependence are determined by a sole factor: the temperature.

Figure 4 gives the spectrum of a black-body radiation at 3 K. This is exactly the present temperature of the thermal radiation of the universe. The radiation is a survived evidence of high temperatures at the start of the expansion of the universe. This is why it is called relic, i.e. one that came from the remote past. The relic radiation of the universe was predicted in 1946 by the Russian physicist George Gamow. He estimated the modern temperature of the universe at 10 K which is very close to the true value.

Figure 4 shows the peak value of the spectral curve of the relic radiation to fall on the wavelength of several millimeters. The same electromagnetic radiation occurs in the radio-frequency range undetectable, certainly, by a naked eye. The three-degree black radiation of the universe was discovered by the American astronomers A. Penzias and R. Wilson in 1965.

A natural question may arise: why modern measurements show such a low Big Bang temperature? The fact is that only helium can persist in liquid state at 3 K: the so-called helium temperatures (the extremely low temperatures) have



ig. 4. The spectrum of thermal radiation of the universe ith temperature 3 K.

ot their name from that specific property of this as. A temperature so low is a poor match for n idea of explosion. Imagine a radiotelescope eceiving the relic radiation. Where does it come o us from? How long ago did it start? Which urface and what material were the source of this adiation?

In this connection we may not fail to mention he uniformity of the universe thermal radiation in all directions. Whatever part of the heaven the radiotelescope is directed at, it receives radiation of the same temperature varying by mere several thousandths. Yet even these insignificant variations have their own reason and explanation as we shall see below.

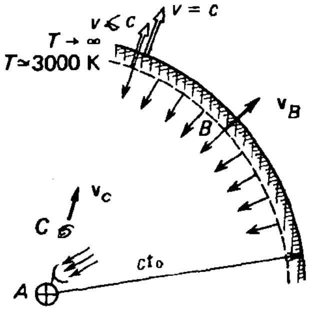


Fig. 5. The diagram of universe expansion and relic radiation propagation.

We shall try to answer the above questions from qualitative positions since their quantitative analysis would require a stricter approach to the notions of cosmology. Consider Fig. 5. The Earth and a radiotelescope receiving the relic radiation are placed arbitrarily at point A. You know already that the modern estimation of cosmological time, t_0, equals approximately 10^{10} years. If we receive today radiation emitted at the moment t_1, we should assume that it has travelled the path $c\,(t_0 - t_1)$. The velocity of light c is the highest possible velocity of information transfer. It is clear that no information can reach us from the distances longer than ct_0.

A part of the sphere of this radius is represented by a continuous arc. The points inside the cross-hatched area are theoretically observable. But the light emitted in this zone is intensively absorbed. This happens because the density and temperature of the material are high at short cosmological time periods: the material is then in the state of plasma and opaque to light.

The recombination of the cosmic plasma, i.e. the composition of electrons and ions into neutral atoms occurred when the universe temperature was approximately 3000 K. The time interval between the *moment of recombination* t_1 and the start of expansion was merely 1 to 1.5 million years. It was then that the universe matter turned transparent from the light-absorbing black. The moment of recombination is expressed in Fig. 5 by the sphere with radius $c\,(t_0 - t_1)$ indicated by dashed lines. It is the radiation of this very surface that is received by radiotelescopes. But why don't we see the red-hot heaven heated to three thousand degrees and do register a temperature thousand times lower?

Recall to mind that the universe does expand. The surface of recombination is relatively close to the limiting sphere with radius ct_0. Thus, it moves away from us at a speed close to the velocity of light. You are familiar with the Doppler effect: if the source of waves moves relatively to the radiation receiver, the received frequency differs from the emitted one. The universe expands, therefore we receive the radiation of expanding galaxies shifted to the red side, the side of longer waves. The surface emitting the relic light moves away very fast at a speed slightly lower than the velocity of light. For this reason all frequencies of the thermal radiation of this surface decrease by thousand times at 3000 K. In the same way falls the detectable temperature, therefore radiotelescopes "see" the radiation at 3 K.

To understand the composition of the universe one should comprehend the uniformity of all its points: the universe is homogeneous. Figure 5 may lead to an erroneous assumption that we are placed in the center of the world. However, the limiting sphere with the radius ct_0 is not a border of the universe: it is merely an expanding sphere of the information we get about the world. For example, the limiting sphere would be different for an observer placed in galaxy C. To illustrate the homogeneity of the universe we shall describe its evolution once again with the origin of coordinates taken at one of the points from which the relic radiation comes to us at the present moment: at point B. We shall de- scribe in succession a part of the universe at various moments of cosmological time, at the stages of expansion when its structure or com- position alter significantly.

We shall start (see Fig. 6a) with the momen only a few seconds after the Big Bang's setoff In this case the order of magnitude of the tem perature is 10^{10} K. At this moment the univers is opaque, the high-temperature radiation emit ted from point B being absorbed at a very sho distance from the source. Certainly, all poin emit radiation, including point A at which o Galaxy would form later. Point A moves aw from point B due to expansion. This stage of th

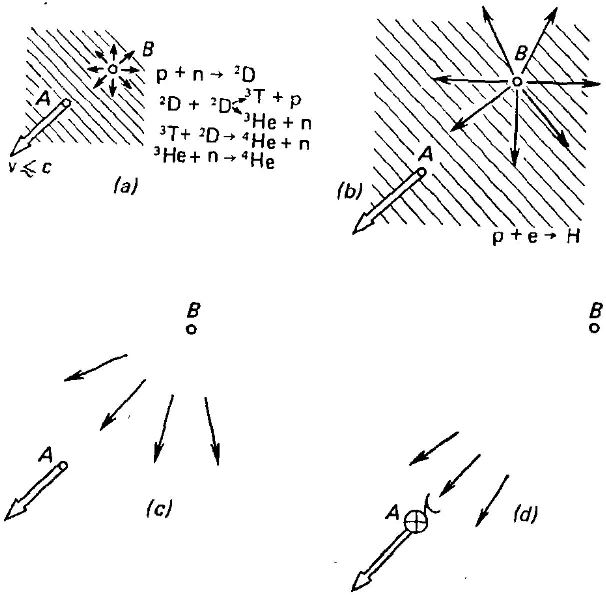


Fig. 6. Propagation of the relic radiation: (a) at the moment of the cosmological synthesis of elements $t \simeq$ 1 s; (b) at the moment of recombination $t \simeq 10^6$ years, $T \simeq 3000$ K; (c) at the stage of the formation of galaxies, $t \simeq 10^9$ years, $T \simeq 15$ to 20 K; (d) modern state: $t \simeq 10^{10}$ years, $T = 3$ K.

evolution of the world is characterized by the formation of the nuclei of the first elements' isotopes (deuterium ^{2}D, helium ^{3}He and ^{4}He, and lithium ^{7}Li) from protons and neutrons. Theoretical studies indicate that this primary synthesis of elements results in 25 to 27% of isotope ^{4}He (by mass), and 73 to 75% of the