The creation of the RDS-37 charge closed the breach in addressing the problem of Soviet thermonuclear weapons, and the charge itself became the prototype for all subsequent two-stage thermonuclear devices in the USSR.

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[2] For more on the history of building the Soviet nuclear shield and the peaceful use of atomic energy, see also Refs [10–25]. (*Editor's note.*)

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History of the Universe History

A M Cherepashchuk

1. Introduction

This review deals with the development of our concepts on the structure and evolution of the Universe. Two revolutions in astronomy will be considered: the transition from the geocentric to heliocentric model, and from the static Universe to the nonstationary expanding Universe, including the early inflation phase. Presently, we are on the eve of the third revolution in astronomy, which is related to the discovery of accelerating expansion of the Universe and the realization of the fact that baryonic matter constitutes only 4% of the total matter density in the Universe. The outstanding achievements of modern cosmology are striking (see, e.g., monographs [1–3]).

It is worth getting back to the basics of astronomy to follow up the development of the modern cosmological model. This is especially important because in recent years a wicked principle, 'onward to the past', is being established in our country. Under the slogan of getting back to old traditions, to the historical roots of our people, paganism and obscurantism are resurging. The materialistic vision of the world is being attacked. Natural sciences disciplines are emasculated from school educational programs. In particular, for more than a decade astronomy has not been taught as a separate subject in Russian schools. A wave of militant obscurantism has engulfed television, radio and other mass media. The natural result is ensuing: according to public opinion polls carried out by The All-Russian Public Opinion Research Center (WCIOM), the proportion of the Russian people who think that the Sun orbits Earth and not vice versa increased in 2007–2011 from 29% to 33% (wciom.ru/index.php?d = 459&uid = 111345). So, one third of the Russian population shares the medieval point of view and, sadly, the number of these people is increasing. Therefore, it seems timely and proper to write the present review.

2. Astronomy — the oldest science

The first signs of early astronomical science go back to 700–800 BCE [4–6]. As a rule, they exhibit points of similarity with observational astronomical areas, astronomical drawings, and images of lunar calendars on the walls of caves. For example, ancient Maya inscribed astronomical cartoons on the walls of caves more than six thousand years ago [7, 8]. Apparently, there are traces of human astronomical practices as early as 2000 BCE: for example, a rod made of mammoth bone was found near Achinsk (Russia), which had the

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number of grooves in the ornament corresponding to different astronomically significant periods [9]. All these traces are related to so-called pre-historic astronomy.

Human astronomical practice described in written accounts is related to historic astronomy. The first evidences of historical astronomy correspond to 2000–3000 BCE [10, p. 26].

In the first millennium BCE, the first attempts to perceive the Universe as an ordered structure and to understand its components, intrinsic laws, and even origin emerge.

The earliest ideas were known from religious cosmophysical 'hymns' — ancient Indian Vedas [11, 12]. For example, in the ancient Indian *Rigveda* — the Vedic collection of hymns (1000 BCE) — one can read that Earth is 'a big flat space' covered by the sky — 'a blue dome' sprinkled with stars [10, pp. 47–51].

One can find attempts to describe the Universe as a whole with flat Earth in the center in ancient Chinese chronicles written by court astronomers, who were respectable civil servants [10, pp. 37–43; 13, pp. 93–104]. But such attempts manifested themselves particularly strikingly and multiformly in scientific work-poems, '*On Nature*' (on the essence of things), written by the first natural philosophers and astronomers in ancient Greece, in which a fairly totalitarian model of power went together with comparatively wide autonomy in thinking [13, p. 107; 14].

Early astronomy, in addition to practical purposes (orientation in space and time, prediction of the beginning of agricultural tasks, etc.), was of a cultic nature. This was expressed as worship of celestial bodies (the initial astral forms of religion) and as an interpretation of the motion of celestial bodies and sky phenomena in terms of messages from the heavens (the origin of astrology).

The observation-based skill to predict the appearance of some periodic phenomena (for example, lunar and solar eclipses) made astronomy a powerful political tool in the hands of priests in totalitarian states (like Ancient Egypt or Babylon in Mesopotamia). Therefore, the cultic astronomical practice of priests was strictly classified.

3. The oldest ideas about 'ordinary' and new forms of matter in the Universe

Ancient philosophers tried to reduce a whole variety of the observed world to a few primordial elements.[1] Usually four essences (principia) were thought as basic.

The first principium was 'earth', which played the central role.

The second principium was 'water' as an eternally moving medium. In 700 BCE, the founder of the Greek science Thales of Miletus thought that the heavy flat cylindrical Earth floats on the water [10, p. 60; 13, p. 109].

The third principium was 'air', as a ubiquitous substance showing its worth in wind and whirlwind. In the 6th century BCE, Anaximenes of Miletus believed that Earth holds on to a whirlwind as the head laying on a pillow [10, p. 61].

The fourth principium was 'fire', the lightest essence which appears in celestial bodies. This point of view was shared by Anaximander (700 BCE), who was the pupil of Thales and the teacher of Anaximenes, as well as by Heraclitus of Ephesus (500 BCE), who was the Pythagorean, fire worshipper and Zoroastrian, the founder of dialectics in philosophy [10, pp. 61, 62; 15, pp. 358–365].

The famous Hellenistic philosopher and astronomer Plato (400 BCE) added to the four 'earth' principium entities (earth, water, air, and fire) a special fifth 'heavenly' entity (the 'quintessence') and called it 'ether' [10, pp. 73, 74].

The ancient Indian natural philosophers (400 BCE) proposed another interesting idea. They assumed that some invisible universal medium, which they called 'prana', possesses properties of executing self-motion and being in the state of a 'tension' (an idea reminiscent of the 'empty' Universe considered by de Sitter) [10, p. 51].

In 500–400 BCE, Leucippus and Democritus first represented matter as consisting of microparticles (atoms), which are distinguished only by size and complexity of the form, without its concretization [10, pp. 67–72].

Plato, the junior contemporary of Leucippus and Democritus, the founder of Athenian Academy, first introduced quantitative characteristics (geometrization) to the notion of primordial matter (it is interesting to note that above the entrance to the academy was inscribed the warning phrase "Let no one ignorant of geometry enter here."). Plato associated each primordial element's particle with one of five regular convex polyhedrons ('Platonic solids'): cube (particles of earth), tetrahedron (particles of air), octahedron (particles of fire), icosahedrons (20 faces, particles of water), and dodecahedron (12 faces, particles of ether) [10, p. 74].

4. Flat Earth in the center of World

It seemed obvious for ancient philosophers that Earth is flat and a man makes himself felt as residing in the center of a spherical vault of heaven. So, the first models of the Universe were geocentric with flat Earth in its center. The very origin of the Universe was not infrequently connected with the idea of a primordial fire (e.g., in ancient India or Greece). Especially notable is the model constructed by Anaximander (700 BCE) [10, pp. 60, 61] (Fig. 1). Anaximander represented the origin of the Universe as a result of overheating the central body

Figure 1. Model of the Universe by Anaximander (700 BCE) with flat Earth in the center.

[1] Later on, this principle was clearly formulated by the English logician and philosopher of the 14th century W Occam: "Entities must not be multiplied beyond necessity". The so-called Occam's razor principle became one of the guiding principles in constructing a theory, and even a signature of its correctness.

('the embryo') and its disruption into several rings ('cosmoses') from some opaque matter, which were filled with the heavenly fire. According to this model, celestial bodies are slots in 'cosmoses'-rings, which transmit the light of the fire. The Universe is also enclosed by an external fire. The Sun and the Moon here are located above the stars. In the center of the Universe, the flat cylindrical (according to Thales) Oecumene (i.e., the habitable Earth) is located, and Greece is placed in the center of Earth. (Similarly, in Mesopotamia the world was centered in Babylon, and in China in the Heavenly Empire; this is the reflection of the even older topocentric world model).

5. Spherical Earth in the center of World

As early as 600 BCE, Pythagoras argued that Earth has a spherical form. This is proved, for example, by the spherical shadow of Earth observed on the disc of the Moon during lunar eclipses [10, p. 64]. Parmenides [10, p. 66] and later Aristotle [13, pp. 126–128] considered the entire Universe globe-shaped, spherical. This idea was inspired not only by the rounded shape of the firmament, but also by the circular diurnal motion of celestial bodies. (It is not for nothing that Greeks considered a sphere to be the most ideal among all possible forms, and a uniform circular motion to be the most ideal among all possible motions).

Aristotle (384–322 BCE) (Fig. 2) was the first to generalize the knowledge accumulated in Greece and abroad about both Earth and space [10, pp. 77–84] into a harmonious geocentric pattern of the World, the first observationally and theoretically validated in the history of natural sciences. Aristotle put Earth, consisting of the heaviest classical element, in the center of the World. The Sun, the Moon, and the five planets known at that time (visible by the naked eye): Mercury, Venus, Mars, Jupiter, and Saturn, rotate around Earth. Each celestial body is associated with the corresponding sphere rotating around central Earth. The body is attached to its sphere and hence also rotates around Earth. The most distant is the eighth sphere, where stars are located. This sphere also rotated around Earth in correspondence with the observed diurnal sky motion. According to Aristotle's physical theory, celestial spheres, as well as celestial bodies themselves, seemed to be made of a sky material — ether, which has no heaviness or lightness and exists in an eternal circular motion.

Ptholemy's mathematical theory (2nd century CE) [16, 17] (Fig. 3) became the peak of the development of the geocentric model of the World. Due to its precision, this theory held for almost two millenia. It allowed very accurate calculations of astronomical tables of the location of celestial bodies (ephemeris), which in the 15th century was used by Columbus and Amerigo Vespucci to make first major geographical discoveries and by Magellan to voyage round the world.

Ptolemy was inspired by his predecessor Hipparchos (200 BCE), the famous founder of Hellenic observational and theoretical astronomy [10, pp. 88–92; 13, pp. 137–142]. Hipparchos was the first to reject the notion of rotating spheres with attached celestial bodies and started describing the motion of celestial bodies in terms of combinations of uniform motion in circular orbits. He used the method suggested by Apollonius of Pergas [10, p. 89] (300 BCE) to represent a nonuniform motion as a sum of two uniform circular rotations. In this method, the body being studied is attached to the secondary circle (epicycle) whose center uniformly moves along the first (carrying) circle, called deferent, so the motion of the body looks nonuniform from the center of the deferent. Hipparchos showed that under certain conditions the motion along two such circles is equivalent to the motion along one eccentric orbit. The center of the latter turns out to be somewhat shifted off Earth. Therefore, Hipparchos was able for the first time to

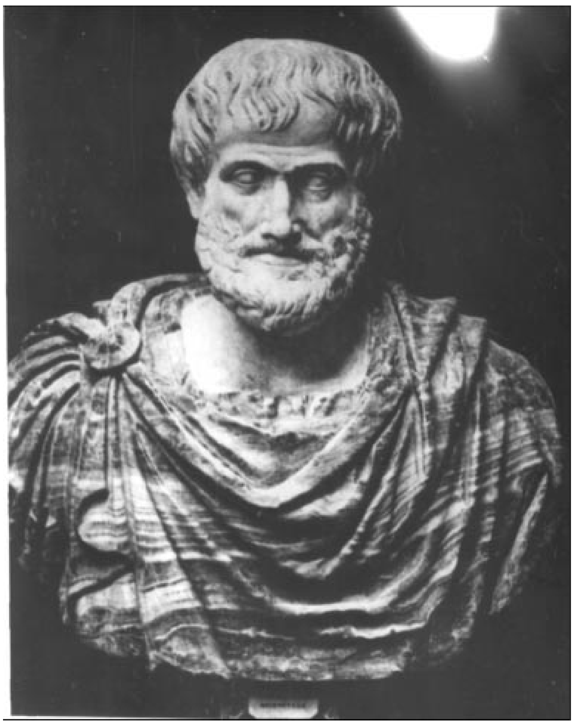

Figure 2. Aristotle (384-322 BCE).

Figure 3. Ptolemy (ca. 90 – ca. 168 CE).

explain the earlier discovered nonuniform visible motion of the Sun (he introduced the apogee and perigee), and later the visible motion of the Moon. However, he lacked enough observational data to study planetary motions.

Ptolemy from Alexandria (Egypt), the famous astronomer and geographer, fully used the heritage of ancient Babylonian astronomers to construct the first mathematically rigorous (geocentric) theory of motion of all luminous celestial bodies (Sun, Moon, and planets), which can be used to quite precisely (for naked-eye observations) calculate the visible locations of these bodies in the sky. But this problem was rather tricky, since, for example, unlike the Sun, planets move in the sky nonuniformly and sometimes even in a looplike manner. A planet can stop moving relative to stars, start moving in the opposite direction, then stop again and return to the original direction of motion. For the observer on immobile central Earth, who believes that he is looking at the planets, it is difficult to explain such a complicated motion of planets. It is quite possible that it is for this reason that the planets at that time were considered to influence the fate of people, which initiated the appearance of astrology.

In Ptolemaic theory [13, pp. 147–157], each planet participates in several circular motions: the center of the secondary circle (epicycle) moves along the first main circle (deferent), and the former in turn serves as a deferent for the center of the next epicycle, etc., and the planet is attached to the last upper epicycle. Notice that the planes of deferents and epicycles may not coincide and some of them can even oscillate. The sum of these motions yields the visible trajectories of motion of the planets among the stars. In terms of modern language, Ptolemy's theory was based on a power-series expansion of visible trajectories of celestial bodies in spherical functions, which typically coincide with Fourier series. As noted above, Ptolemaic mathematical theory was invariably capable of explaining and predicting with good accuracy the positions of the planets in the sky and was extensively used for over 14 centuries (if counted from the Ptolemy epoch). The Ptolemaic system was consecrated by the Catholic Church and seemed unshakeable. This is why Arabic astronomers called the collection of Ptolemy's works *Almagest* (the Greatest). Ptolemy himself called it much more modestly: *Mathematicae Megale Syntaxis* (The Great Mathematical Treatise) [10, p. 93]. Already in the 5th century, Ptolemy's works were commented on by Indian astronomers. And in the 7th century, after the downfall of Antic Civilization, astronomers of the Middle East, who obtained Ptolemy's writings as a military trophy, preserved them, and after that these writings became available for the entire world.

With a strengthening of new monotheistic religion, Christianity, Aristotle's geocentric system, which was quite scientific for its time, as was the Ptolemaic system, too, was first violently denied by the Catholic Church (as any heathen Hellenistic heritage). But in the 13th century (on the suggestion of the far-sighted theologian Thomas of Aquino, who discerned in these systems a pillar for Christianity [10, p. 122; 18, pp. 107–109]), both these systems were combined into unified teaching and turned into a religious dogma, which hampered the development of natural sciences for centuries.

The Ptolemaic theory itself, which with the discovery of new nonuniformities in the motion of celestial bodies was overgrown with newer and newer epicycles (by the beginning of the 16th century their number reached 80), gradually became exceedingly awkward, which signaled the approaching crisis in the general astronomical picture of the world. In the Medieval East (before any contact with the West) there were attempts to improve the Ptolemaic theory: to this end, Nasir al-Din Tusi [10, pp. 115, 116] rejected in the 13th century the most ingenious of Ptolemy's inventions — the introduction of equant, which was essentially a prototype of the Kepler's second law, thus taking a step backward, and two centuries before that the encyclopedist Al-Biruni even vaguely spoke about the possibility of Earth's motion [19].

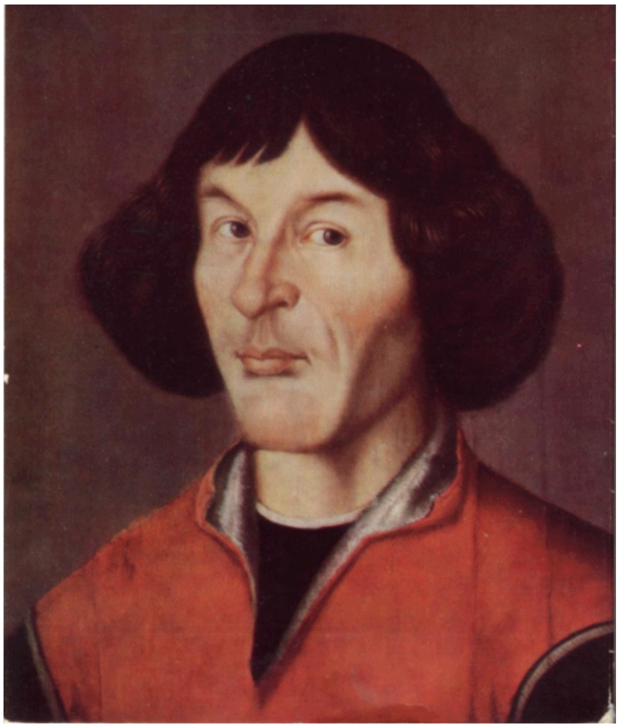

Figure 4. Nicolaus Copernicus (1473–1543).

In the 13th–14th centuries, in western Europe, despite the Church's prohibition, ideas of the noncentral location and even motion of the Earth also get emerged. In the middle of the 15th century, the German mathematician, philosopher, cosmologist, and greatest theologian Nicolaus von Kues (Nicolaus de Cusa) (1401–1464) (who obtained the high Roman cardinal rank exclusively due to personal achievements), in his famous work *De Docta Ignorantia* (*On Learned Ignorance*) (1440), presented his own cosmological concept of an infinite isotropic Universe [20], by writing: "The center of the Universe is everywhere, and the boundary — nowhere", and later: "None of the stellar areas lacks life." One and half centuries later, his spiritual successor, Giordano Bruno, developed this philosophical concept up to the level of striking concrete astronomical previsions.

6. Heliocentric system of the World by Nicolaus Copernicus

The greatest Polish astronomer, Nicolaus Copernicus (1473–1543), was the destructor of the apparently unshakeable geocentric system [21–23] (Fig. 4). Fascinated by Ptolemy's mathematical genius as early as his studentship at Krakow University, Copernicus soon realized the main flaw in the Ptolemaic geocentric model: it violated the main methodological principle of Occam's razor. Indeed, each heavenly body required an individual system of epicycles not related to other bodies, which made the theory not only awkward but also intrinsically broken into pieces: there was no single reason for the visible regularities in the motion of the celestial bodies. In his historical searches, Copernicus found ideas of ancient philosophers that there can be another reason of the observed phenomena — the motion of the observer himself together with Earth around another center of the world (a mythical central holy furnace — Hestia — in Pythagoreans (600–500 BCE [10, p. 64]), or around a much more realistic body — the Sun — in the hypothesis of Aristarchus of Samos from Alexandria (300 BCE) [24]).

Copernicus started working with gusto on a new theory even during the continuation of his education in Italy at the beginning of the 16th century. He was also encouraged by a request made to him, as a great mathematician and astronomer, by the fathers of the Church after the Fifth Council of the Lateran (1512), asking him to upgrade the Julian calendar, which strongly deviated by that time from the solar calendar and thus hampered calculations of the main church feast-day, Easter. (This reform would require first of all improving the theory of motion of the Sun and Moon.)

Therefore, the intrinsic logic of science for Copernicus was the primary driver to develop a new theory of planetary motions. He was also motivated by practical needs of his time, which is characteristic for the history of advancement of fundamental sciences at all. Modern Russian high-ranking officials, however, frequently require scientific research to be entirely motivated by practical needs. For example, the Vice Chair of the Science and Technology Committee of the State Duma of the Russian Federation says: "Coming from market requirements, industry must pose problems for applied science, and applied science, in turn coming from market conditions, must pose problems for fundamental science. This requirement should determine the financing of fundamental science." Thus, the well-known facts that science has its own laws of development and scientific knowledge has its own value are ignored.

The motion of Earth around the Sun was the key point of Copernican theory. To achieve the necessary accuracy in describing planetary motions, he had to preserve a certain number of epicycles in his heliocentric theory (but only 34 of 80). The fact is that the real orbits of planets are elliptical, and their orbital motion is nonuniform. However, Copernicus traditionally considered only uniform motions and circular orbits. Since the observer in his system of World watches the motion of planets from the moving Earth, the apparent complex looplike planetary motions simply reflect the annual revolution of Earth and result from summation of velocity vectors of Earth and the planets.

This theory, in addition, fully discarded the mystical role of planets and deprived astrology of its ideological basis. One has to only wonder how persistent medieval prejudices are even in modern Russia, where astrology, this dirty business based on phrase-mongering and insolent fraud, prevails on almost all TV channels. Astrological 'predictions' are harmful, from both the moral and economical points of view: up to one third of profitable contracts have been lost by Russian business people simply because astrologists do not recommend making business in that day... .

Thus, thanks to Copernicus, we learned that not Earth, but the Sun, resides in the center of our planetary system.

The basics of heliocentrism were set forth as a preliminary by Copernicus in the manuscript *Commentariolus* (1515) [25]. The new theory was fully developed in his main writing, which had been completed by 1530, but was published many years after, under pressure from his friends, who where eminent and educated clerics. The detailed popular account of this theory, entitled *Narratio primo*, was published before that data by Copernicus's pupil Rheticus in 1539 [26] and was later widely referred to as an intelligible source of information about Copernican heliocentric theory (the strict theory was mathematically difficult to perceive by most readers). The complete work of Copernicus, *De Revoutionibus Orbium Coelestium*, consisting of six large sections, or 'books' and printed in Nuremberg [27], was given to the dying Copernicus on the day of his death on 24 May 1543. After Copernicus, it was impossible to consider Earth to be located in a selected place in space, like some 'divine pedestal'. Our location in space is not remarkable. This general statement is usually referred to as the 'Copernican principle'. Essentially, Copernicus 'discovered' Earth anew as being the ordinary sixth planet of the Solar system (which, however, has been selected to host life). Copernicus's differentiation of planetary motions into apparent (because of the motion of the observer) and proper stimulated searches for laws of these true planetary motions, which were discovered by Kepler at the beginning of the 17th century. These laws were justified subsequently by the founders of modern mechanics, from Galileo to Newton, who deduced all three laws of planetary motions from the universal law of gravitation.

There was a principal unanswered question in the Copernican theory. If remote stars are located at different distances from Earth, then, due to Earth's orbital motion around the Sun, one should observe regular parallactic shifts in the location of nearby stars relative to more distant ones. These shifts could not be observed in Copernicus's time. Copernicus explained this fact by the almost infinite location of the stellar sphere — in the same way as his Hellenic predecessor Aristarchus of Samos did. The first stellar parallaxes were successfully measured only three hundred years later [28] by a Russian astronomer, V Ya Struve (for star Vega, α Lyr, 1837), by a German astronomer, F Bessel (for the star 61 Cyg, 1838), and by an English astronomer, T Henderson (for α Cen in the southern sky, somewhat earlier than 1839, but published only after his return to England). All three parallaxes were about a few fractions of an arcsecond. This evidenced that the stars are located at huge distances from our planet: even from the closest one (α Cen) it takes 4.3 years for the light to travel to Earth.

Already in the first decades after publication of the manuscript, the new Copernican theory started to 'work' as a more effective method of mathematical description of motion of celestial bodies. In 1551, a German astronomer, E Reinhold, calculated the first heliocentric planetary ephemeris, known as the "Prutenic Tables" [10, pp. 140, 150]. In 1582, finally, the calendar reform was realized (the new Gregorian calendar was substituted for the obsolete Julian one). At several universities in the 1580s, some astronomers started giving lectures based on the heliocentric system (the first was a Swiss professor of mathematics and theology, astronomer, and historian of science, C Wursteisen, who was later highly estimated by Galileo). This free initial propagation of the Copernican theory was also due to the preface to Copernicus's book, moderating its revolutionary essence, written by the Lutheran theologian Osiander, who presented this theory simply as a new mathematical model of the World.

However, already in 1616 the Copernican theory was banned by the Catholic Church. And later, the heliocentric system, including the true laws of planetary motion discovered by Kepler at the beginning of the 17th century, made headway with difficulties. The official Church ban persisted for more than 200 years until 1828. In the same 1580s, the true revolutionary meaning of Copernican theory was recognized as a system of the world clearly contradicting the Bible and Christian dogmas. The Catholic Church was the first to show a furious intolerance to this new theory. Its representatives, professors of European universities, were brought to shame in public debates by the first enthusiastic propagandist of the new system of the World, Giordano Bruno, a former monk escaped from a Neapolitan abbey, who struck the audience with his knowledge, intelligence, challenging ideas, and ability to persuade.

7. Fight for heliocentrism

A genial Italian philosopher, Giordano Bruno (1542–1600) (Fig. 5) was the first fighter for heliocentrism, who also deepened and widened its sense. The successor of Nicolas of Cusa in cosmology, Giordano Bruno appreciated the mathematical sense of Copernicus's theory but also was the first to understand its ontological limitations, because Copernican heliocentrism asserts the central position of the Sun in the Universe. Bruno claimed that the Sun and Solar System are one of many similar systems in the Universe, and, following his spiritual teacher, started spreading the challenging idea about many habitable worlds. In his principal cosmological work, *De l'infinito universo et Mondi* (*On Infinity, the Universe, and Worlds*) (1584) [24], Giordano Bruno developed new ideas on the Universe and on the self-motion of celestial bodies in it. In a visionary way, he called his doctrine 'the philosophy of dawn.' He described the Universe as consisting of many suns with orbiting planet systems, on which life is also possible. Such a 'blasphemy' could not be tolerated by the Catholic Church. Betrayed by the traitor to the Inquisition, Giordano Bruno was jailed, and after unsuccessful attempts to make him retract his 'misconceptions', in 1600 he was burned at the stake for heresy at Campo de Fiori in Rome. (At the end of the 19th century, a monument was dedicated to him; the inscription on the base reads: "To Bruno — the century predicted by him — here where the fire burned").

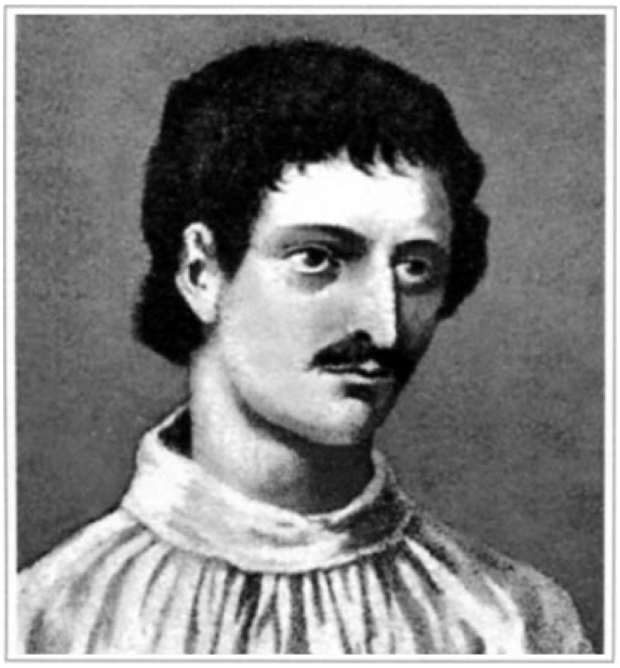

Figure 5. Giordano Bruno (1548–1600).

In the accusatorial records of tens interrogations of Bruno in the Roman jail where he spent the last seven years of his life, the propaganda of the multiplicity of habitable worlds was the scientist's main incrimination. However, equally painful and intolerant to the Church was Bruno's criticism of the principal dogmas of the Church, especially his direct appeals to the Venetian government to secularize the illimitable wealth of monasteries (which he personally witnessed). We see that time goes on, but nothing has changed...

We shall hope that the current fascination with 'old traditions' will not lead to a repetition of similar actions against contemporary Russian scientists: when in 2007 the top 10 Russian academicians signed a letter to the President of Russia against the imposition in Russian secondary schools of the 'Basics of Orthodox Culture' discipline (read: 'God's law'), articles appeared in some press media calling for these impudent 10 academicians to be brought together to the place of execution in Moscow's Red Square and to have their heads chopped off.

Recently, 'Orthodox activists' have requested that astronomy be banned, since it undermines the trust in God (http://kremlnews.ru/posts.html?p2_articleid = 1502). Thus, modern Russian radical clerics want the laurels of ancient Egyptian priests who, as noted above, kept astronomical knowledge top secret to improve their own political and economic power. How astonishingly close epochs separated by thousands of years turn out to be!

Several years ago, V I Arnold, at a reception by Pope John Paul II in the Vatican, asked: "Galileo was recently freed from a charge by the Church. Is it timely to justify Giordano Bruno as well?" The Pontiff replied: "Why not? But first prove the existence of life on other planets." Now more than 2000 exoplanets have been discovered around other stars in the Galaxy. Efforts are being made to find signs of life on other planets, in particular, searches for spectral lines of oxygen, methane, water vapor, and carbon dioxide in planetary atmospheres are underway, which can signal the presence of organic life.

The strongest impact on the obsolete geocentric world system — but this time using astronomical observations — was made by Galileo Galilei (1564–1642) (Fig. 6), who was the founder of telescopic astronomy.

Spectacles with convex lenses were invented in Italy as early as the end of the 13th century. In 1450, again in Italy, spectacles with concave lenses were designed. By the beginning of the 17th century, craftsmen appeared in different countries who achieved great success in grinding and polishing glass lenses. The first spy-glass with an ocular — a negative lens, which produced a direct image — was invented at the beginning of the 1600s in Holland. This device is credited to opticians Jacobus Metius, Zachariah Janssen, and Hans Lippershey, who even tried to take out governmental patent on it as an important military device. Spyglasses soon hit the stores [30].

After finding out about this device, in 1609 Galileo, being a talented engineer, constructed by description a similar spyglass of his own (by increasing the magnification from 8 to 32 times), and was one of the first to look at the sky with it. However, it was Galileo who saw and realized, in contrast to

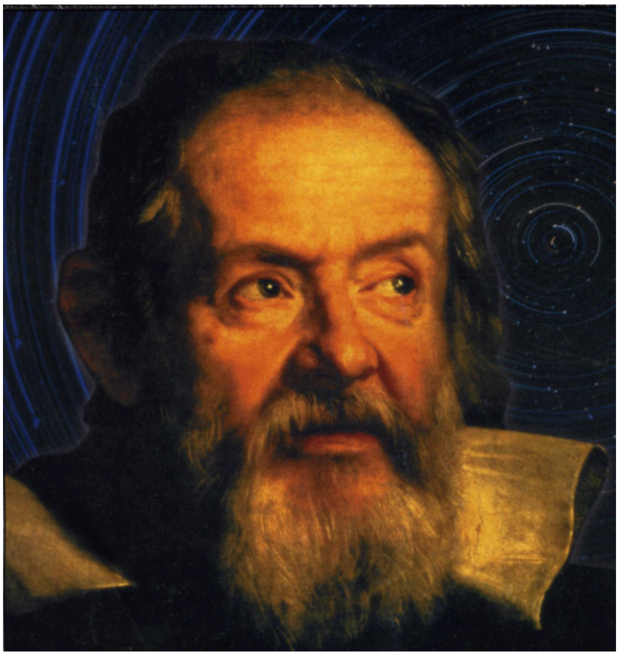

Figure 6. Galileo Galilei (1564–1642).

other observers, that these observations not only reveal the true nature of the celestial bodies, but also confirm the Copernican theory. Starting his observations at the beginning of 1610, Galileo published the first results as early as March of the same year in his famous *Sidereus Nuncius* (*The Starry Messenger*) [31]. He saw mountains on the Moon, discovered individual stars in some 'clouds' of the Milky Way, and later discovered phases of Venus (which were impossible from the geocentric viewpoint). He was also the first to discover solar spots. However, the main sensation in *The Starry Messenger* was the discovery of new bodies orbiting other planets — four Jovian 'moons'. It was the first time the geocentric system was disproved (since the only center of revolution was thought to be Earth) and undeniable evidence of a heliocentric world system. After this discovery, Galileo became a strong defender of the Copernican system.

It was just in 1616, soon after Galileo had written a letter to his pupil Castelli on solar spots (1613), where he clearly inclined to the opinion that Copernicus was right, that the Catholic Church banned propaganda of Copernicus's heliocentric theory (unless it was used simply as a convenient mathematical tool). Copernicus's writing was included in the famous *Index Librorum Prohibitorum* (*List of Banned Books*). After much effort, Galileo obtained permission from the Vatican to publish more cautious considerations about the Copernican theory. In his fundamental writing, *Dialogo dei Due Massimi Sistemi del Mondo* (*Dialogue Concerning the Two Chief World Systems*) (1632), published in comprehensive Italian in the traditional form of a quiet talk between three scientists [32], he convincingly showed the advantages of the heliocentric system. This prejudged the later fate of the scientist. His work was almost immediately banned, and the author was subjected to punishment from the Inquisition. In 1633, Galileo was summoned to Rome, arrested, and publically judged, during which in a humiliating form (under the threat of torture), the 69-years-old scientist had to recant his 'misconceptions'. Galileo spent all the rest of his life under house arrest and surveillance by the Inquisition in a small estate at Arcetri near Florence. One of the misdoings

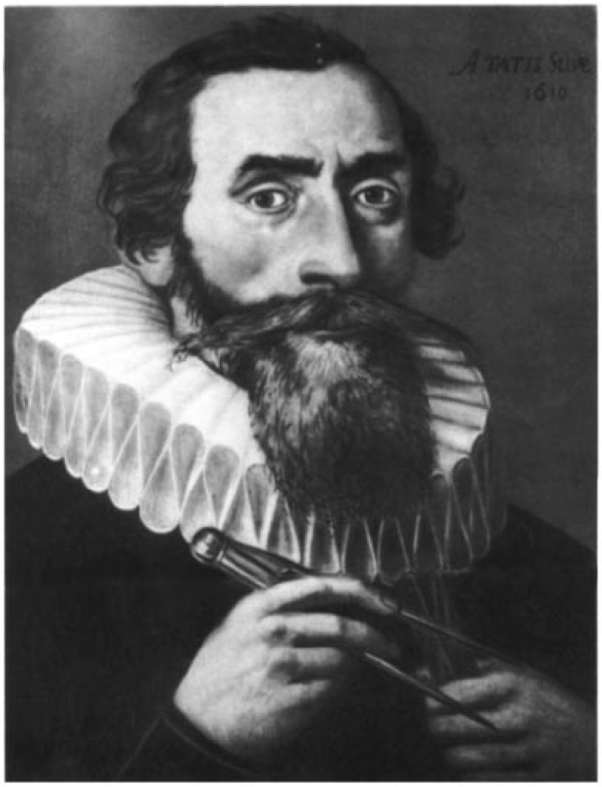

Figure 7. Johannes Kepler (1571–1630).

incriminating Galileo concerned the form and style of his writings. Galileo's writings were understood by the ordinary people, which was shocking. Nevertheless, Galileo's spirit was unbroken, and he managed to publish the second edition of his work in more tolerant Holland [33] (which, apparently, gave rise to the legend about the phrase he uttered before the Inquisition: ''Eppur si muove!'' (And yet it moves!)). The year 2009, the 400th anniversary of the invention of the telescope and first observations by Galileo, was announced the World Year of Astronomy [34].

In 1609–1619, another convinced successor of Copernicus, an outstanding German astronomer and friend of Galileo, Johannes Kepler (1571–1630) (Fig. 7), discovered three laws of true planetary motion. His discovery was based on rich observational data, mostly related to the motion of Mars, which were obtained and left to him by the great Danish astronomical observer Tycho Brahe (1546–1601). Kepler worked as a calculator in Brahe's observatory in the last years of Brahe's life. These three laws of planetary motions are now well known. The first states that each planet moves in an elliptical orbit around the Sun, located in one of the ellipse's focuses. The second law describes the character of change of the velocity along such an orbit. The third law establishes a beautiful mathematical relation between the period of a planet's revolution around the Sun and its mean distance to the Sun. These discoveries put an end forever to the 'round' planetary orbits and eventually the thousand-year domination of the geocentric system.

After Galileo's and Kepler's discoveries, the first revolution in natural sciences (which started in astronomy with the transition from the geocentric to heliocentric system) continued its glorious development.

The knowledge of laws of planetary motions allowed Sir Isaac Newton (1643–1727) (Fig. 8) to discover the law of universal gravitation. Newton was the greatest English

Figure 8. Isaac Newton (1643–1727).

physicist, mathematician, astronomer, inventor and designer, as well as chemist and metallurgist. He solved a very difficult inverse problem: from the consequences of some process (motion of a planet), he restored the underlying reason. The reason was the famous law of universal gravitation. Newton first proved the action of this law (at least at distances smaller than the distance to the Moon) in 1666. Using the law of universal gravitation, Newton constructed a new cosmophysical picture of the infinite Universe, which he presented in the third part of his fundamental *Philosophiae Naturalis Principia Mathematica* [35] published in 1687. Improving Newtonian law of gravitation has been attempted many times. For example, in the middle of the 18th century, the French scientist Alexis Claud Clairaut introduced an additional term ε/r^3 to Newton's law in an attempt to describe the very complicated motion of the Moon (which is subjected to comparable attraction from the Earth and Sun; for a long time astronomers were worried about a secular acceleration of the Moon). Later on, Clairaut had to reject this idea. The secular acceleration of the Moon was explained by P S Laplace (1787), who proved that this, as well as other enigmatic inequalities in the Solar system, which seemed dangerous for its stability, is a periodic perturbation. It should be noted that even nowadays in respectable scientific journal one can find not infrequently papers suggesting different modifications of Newtonian dynamics (for example, Modified Newtonian Dynamics, MOND). This is done, for example, with the aim of explaining very fast motions of galaxies in clusters without invoking the hypothesis of dark matter. However, it should be emphasized that all variants of MOND bear one general shortcoming: for each galaxy and each galaxy cluster, one should individually modify Newton's law of gravity, which makes MOND less attractive.

With the discovery of the law of universal gravitation, the idea of long-range central forces, including universal gravitation, which act apparently instantly through empty space, was established in physics for a long time. It was rapidly forgotten that Newton himself assumed that the emergence of gravitational interaction requires some mediator. To tell the truth, he allowed for not only the material but also the nonmaterial nature of the mediator for gravitation.

The new physics advanced by Newton was highly estimated by the great Russian scientist-encyclopedist, poet, statesman, and founder of science in Russia, Mikhail Vasil'evich Lomonosov (1711–1765), although simultaneously he was one of the last Cartesians and accepted, following Descartes, the explanation of heat by the motion of particles-atoms. As a progressive thinker, Lomonosov was the successor and even defender (which was relevant in Russia of that time) of the Copernican theory and the idea of the multiplicity of worlds. In rich poetry, Lomonosov described an impressive picture of the Universe, which has unified laws and is filled with hotbeds of life and intelligence: "An abyss opened, filled with stars, stars have no number, the abyss has no bottom." Lomonosov's discovery of the atmosphere on Venus during its passage across the Sun in 1761 [36] was important for recognizing the unity of natural laws.

An academician from St. Petersburg, F U T Epinus, was a striking propagandist of the analogous ideas of planetary evolution and a fighter against 'cometary' superstitions. He was a recognized physicist and the author of the first theory of lunar volcanism. By analyzing the heat distribution over Earth, in 1761 he also predicted the discovery of the southern polar continent — Antarctica. In 2009, upon the initiative of the Sternberg State Astronomical Institute of Moscow State University (MSU), a lunar crater in the north polar region of the Moon was named after Epinus.

8. Universe — the realm of stars. Our Galaxy

According to Giordano Bruno's hypothesis, the Sun is one of the stars in the Universe. In the 18th–19th centuries, scientists identified our Galaxy with the whole Universe. Therefore, all efforts of astronomers at that time were aimed at studying the structure and kinematics of the Galaxy.

William Herschel (1738–1822) was one of the most active researchers on the structure of the Galaxy [37]. He was an outstanding observer who himself constructed telescopes and reflectors with mirrors made of bronze (the largest of his telescopes had a diameter of 1.26 m and a focal length of 12 m). Using his telescope, Herschel discovered a new Solar system planet, Uranus, as well as visual double stars in the Galaxy. Components of such a binary move in elliptical orbits around a common center of mass due to mutual attraction, in accordance with Newton's law of gravity.

The construction of a model of our Galaxy based on stellar counts ('deep sky surveys') was one of Herschel's principal scientific achievements. Herschel drew the model of the Galaxy in a lentillike form with the Sun at the center. Later on, American astronomer H Shapley put the Sun at a distance of 8 kpc from the Galactic center and thus confirmed once again the Copernican principle: our Sun is an ordinary star among a hundred billion stars in the Galaxy occupying an unprivileged (noncentral) position within the Milky Way galaxy. In 1784, Herschel started global deep sky surveys to understand the global structure of the Galaxy and discovered more than 400 new nebulae. He also suggested the model of the island Universe.

By the end of the 19th–the beginning of the 20th century, our Galaxy was being studied in detail. Its size was determined to be about 100 thousand light years and its stellar populations were studied (stars of the disc, intermediate and spherical components). Also studied were stellar clusters (globular and open clusters) and nebulae. Spectral classification of stars was performed, which resulted in the appearance of the famous Hertzsprung–Russell diagram for stars, which has a deep evolutionary meaning.

Different types of variable stars were investigated, including pulsating stars — Cepheids. The construction of the period–luminosity dependence for Cepheids served as a powerful tool to estimate distances to stars. Studies of visual, spectral, and eclipsing binary stars enabled astronomers to reliably estimate the masses, radii, and luminosities of stars of different spectral classes. These findings were used to construct the mass–luminosity relationship for stars, which was used to check our basic concepts about the internal structure and evolution of stars.

9. Edwin Hubble. Beginning of the second revolution in astronomy: the Universe — the realm of galaxies

The question on the true size of the Universe became most essential at the beginning of the 20th century, when scientists started thinking about the nature of numerous nebulae observed by their telescopes. In 1920, the famous discussion between the two most authoritative American astronomers, H Shapley and G Curtis, took place [38]. The discussion concerned the nature of nebulae. Shapley argued that all nebulae are gaseous formations in our Galaxy. In contrast, Curtis believed that many nebulae represent individual galaxies consisting of billions of stars which are located far away from our Galaxy. According to Curtis, our Universe was the realm of galaxies, and its size is much larger than that of our Galaxy. Each of these outstanding astronomers presented observational and theoretical arguments in support of their concepts; however, they were unable to come to a definitive conclusion.

In 1917, a 2.5-m telescope, the largest at that time, was installed at the Mount Wilson Observatory in California (USA). An outstanding astronomer of the 20th century, Edwin Hubble (Fig. 9), started observations with this telescope. Using the photographic method and choosing the best nights for seeing, in 1923–1924 Hubble for the first time resolved individual stars in three spiral nebulae, including the Andromeda nebula (M31). Among these stars, he discovered a special class of variable stars — Cepheids (by that time, a method of pretty accurate determination of distances to these physically variable pulsating stars had already been worked out by analyzing the period of star's brightness variations). Using this method, Hubble was able to estimate the distance to the nearby M31 galaxy, which turned out to be 900,000 light years (the modern estimate yields 2.4 mln light years). Thus, Hubble proved that the famous Andromeda nebula, which one can see with the naked eye in the moonless autumn sky, is extragalactic and represents a giant stellar system comparable to our Milky Way in size [39]. Therefore, the newly commissioned large telescope pushed out far away the boundaries of the Universe, which turned out to be the world of galaxies. Galaxies in the Universe often form galactic clusters, which comprise a few hundred to several thousand individual galaxies. In turn, galactic clusters form superclusters — the largest structures in the Universe. Our Galaxy, together with the Andromeda nebula and about four dozens of other smaller galaxies, form the Local Group of galaxies. The Local Group belongs to the Virgo galactic cluster, and this cluster, together with several other clusters, forms a supercluster, called the Local supercluster, with a size of many tens of millions of light years. Other clusters and superclusters have similar structures. Superclusters are the largest structures observed in the Universe. But most important is that clusters and superclusters are uniformly distributed on average in space. A space region 300 mln years in size, starting from which the density distribution can be considered uniform, is called the homogeneity cell. If we thoughtfully 'smear out' the luminous (baryonic) matter uniformly in a homogeneity cell, we obtain a very low density on the order of 10^{-31} g cm^{-3}, which corresponds to two hydrogen atoms in a 10 m^3 volume.

Figure 9. Edwin Hubble (1889–1953).

Thus, Hubble's discovery once again confirmed the Copernican principle: not only our Sun in the Galaxy, but the Galaxy itself has no preferred location and is one of many billions of galaxies in the Universe. The recognition of the Universe as a homogeneous (on average) world of billions of galaxies has been a genuine breakthrough in science, comparable in value to the Copernican revolution.

10. Origin of relativistic cosmology: Einstein and Friedmann

In 1916, Albert Einstein (1879–1955) (Fig. 10) published the paper on general relativity theory (GR) [40]. In the next year, he published his first cosmological paper [17], in which he developed a theory of a stationary Universe with the cosmological Λ term. At that time, Einstein, along with other scientists, considered our Universe to be a stationary system containing hundreds of billions of stars. However, to his surprise, GR did not allow stationary solutions. That is why, Einstein was forced to introduce a new term into his equations, which he denoted as the cosmological constant Λ. Einstein's Universe described in his first cosmological paper of 1917 comprises a static eternal universe lacking evolution. Its three-dimensional space is non-Euclidean and is topologically similar to a sphere (more precisely, a hypersphere). Einstein

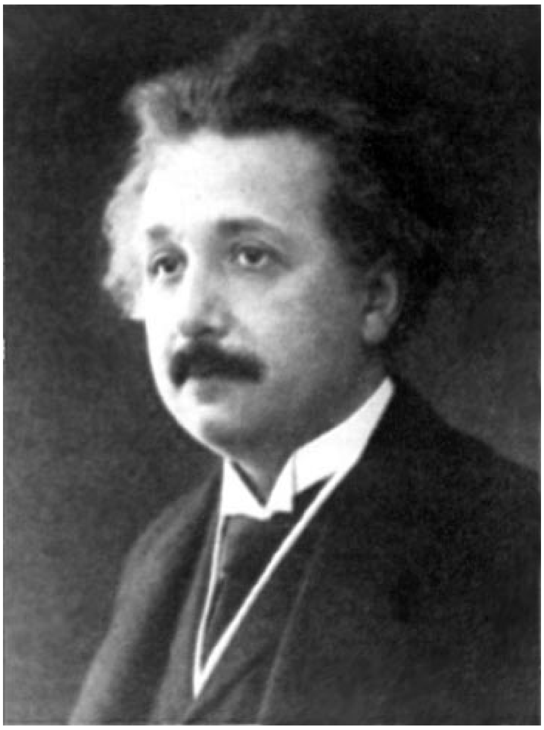

Figure 10. Albert Einstein (1879–1955).

Figure 11. A A Friedmann (1888–1925).

thought that this space should have a finite volume and be closed in itself. Apparently, Einstein was not fully satisfied with his theory. At the end of his paper [41], he emphasized once again that the cosmological constant "is necessary for the purpose of making possible a quasistatic distribution of matter, as required by the fact of the small velocities of the stars".

Alexander A Friedmann (1888–1925) (Fig. 11) was the first to point out the possibility of cosmological expansion of the Universe. In 1922, seven years before Hubble's discovery of the expanding Universe, Friedmann considered modified GR equations (with the Λ term) and showed that they not only allow a static world, but also a world that can expand or contract as a whole. Friedmann developed his cosmological models in two papers: "On the curvature of space" [42] in 1922, and "On the possibility of a world with constant negative curvature" [43] in 1924 [see also his popular scientific book *World as Space and Time* [44] (1923)]. When describing the time behavior of the world, Friedmann notes: "The variable type of the Universe submits a variety of cases for consideration. The cases are possible for that type where the radius of curvature of the world ... monotonically increases with time. There are also possible cases where the curvature radius changes periodically: the Universe contracts to a point (nothing), then again its radius increases up to a certain value, and then again decreases to contract into a point, etc." [44].

In 1922, Friedmann's paper [42] on the theory of a nonstationary Universe was criticized by Einstein [45]. In the next year, however, Einstein revised his point of view, and in a note [46] published in the same journal he wrote: "I consider Friedmann's results correct and shedding new light". Indeed, Friedmann's paper was the first to introduce dynamics and evolution into cosmology. Similar to Copernicus, who 'made' Earth move (rotate around the Sun), Friedmann 'made' the Universe move (expand).

Independently from A A Friedmann, a Belgian astronomer-theorist, G Lemaître (1894–1966), who had recently been a student of A Eddington and later became a member and the President of the Papal Academy of Sciences in the Vatican (he was an abbot), after studying work by Slipher and Hubble on measurements of redshifts in remote galaxy spectra, explained this fact in terms of expansion of the Universe as a whole [47]. He developed his theory more fully in 1933 [48]. Lemaître elaborated his own model of the change of the curvature radius of the Universe with time and considered the growth of perturbations in cosmological models, which preceded galaxy cluster formation.

11. Hubble's law

In 1927–1929, Edwin Hubble discovered that galaxies are not stationary in space but recede from us and from each other (excluding nearest neighbor galaxies such as the Andromeda nebula). Already in 1917, an American astronomer, Vesto M Slipher, wrote about "the recession of cosmic nebulae" [49, 50] (exactly in the year of Einstein's publication on static Universe theory [41]!). Slipher discovered a remarkable fact: 11 of 15 spectroscopically measured nebulae showed redshifted lines, and the weaker the nebula, the stronger the redshift in the spectra. Such a redshift, if interpreted in terms of the Doppler effect, would indicate the recession of galaxies. However, both distances to nebulae and their true nature were unknown at that time, so Slipher did not write a word about cosmology. Nevertheless, seven years later, in 1924, and two years before Hubble's discovery, Friedmann discussed Slipher's observations at one of his seminars at Petrograd University and considered this discovery in the cosmological context, which for the first time directly supported the theory of an expanding Universe (according to D D Ivanenko [51], who attended this seminar). Slipher's discovery was also reported in a popular scientific journal, *Mirovedenie* (1923, April issue), which was published in the USSR at that time.

By 1927, Hubble knew from his observations that many nebulae actually are remote galaxies. In addition, by observing variable Cepheids and the brightest stars in nearby galaxies, he was able to determine the distance to many of them. Using radial velocity data published by Slipher and also those obtained by Hewmason [52], Hubble produced the dependence of the recession velocity V of galaxies on distance R to them. Thus, he worked out his famous law [53]

$$V = HR\,,$$

which is known by right as the Hubble law. The present-day value of the Hubble constant H is ~ 70 km s^{-1} per Mpc. Therefore, Hubble proved empirically that our Universe is expanding and described this expansion in quantitative terms: the velocity of expansion is directly proportional to the distance to a galaxy. Exactly this law was predicted by Friedmann's cosmological model. Hubble's remarkable discovery forced Einstein to withdraw the Λ term from his GR equations. In 1934, Einstein wrote, with caution [54]: "...when considering the cosmological problem it seems natural for the time being to refuse to introduce a cosmological constant — at least until empirical evidence emerges". We have to simply be fascinated by the ingenious prevision of Einstein — in 1998, the accelerating expansion of the Universe was discovered, which again required an analog of the Λ term to be introduced into GR equations. It is interesting to note that Hubble himself had doubts when interpreting his own observations of the redshift effect in the spectra of galaxies. Many years after his cosmological discovery, he suddenly claimed at a meeting of the American Astronomical Society that there is no in fact cosmological expansion of the Universe, and the observed redshift in galactic spectra is a result of 'ageing' of the light quanta travelling from the emission source to the observer. This idea strongly contradicts the basics of modern theoretical physics. In addition, evidence has been obtained in recent years that the volume of the Universe is indeed increasing with time, i.e., the Universe is actually expanding (see Section 17).

12. George Gamow's Big Bang theory

The observed value of the expansion rate of the Universe, given by the Hubble constant $H \simeq 70$ km s^{-1} per Mpc, implies an age of the Universe of about 14 billion years. What was the Universe at the beginning of its expansion? If we start several minutes after the initial, apparently singular, state of the Universe, the following evolution can be accurately traced using the well-known laws of physics. This was first done by an outstanding astrophysicist of the 20th century, George A Gamow (1904–1968), a Russian scientist who had emigrated to the USA in 1933 (Fig. 12).

Friedmann discovered the dynamics and geometry of the world, while Gamow introduced thermodynamics and nuclear physics into cosmology. In 1948, Gamow proposed the theory of the hot Universe (Big Bang), which allowed him to predict (together with his pupils Ralph Alpher and Robert Hermann) the existence of the cosmic microwave background (CMB) [55] (termed also 'relic radiation' by I S Shklovsky in the 1970s). According to Gamow, the CMB with a present-day temperature of 1–10 K represents the residual radiation preserved in the Universe from very early times of its expansion. Gamow was motivated by the desire to explain the origin and abundance of chemical elements. According to Gamow, the initial explosion (called 'Big Bang' by Fred Hoyle) occurred simultaneously everywhere and filled space with hot radiation and matter [56]. At an age of 200 s, the temperature of matter and radiation dropped to about 1 billion K. At such temperatures, helium nuclei were intensively synthesized from hydrogen. In this way, Gamow hoped to explain the abundance, not only of hydrogen and helium, but also of heavier elements (oxygen, carbon, silicon, etc.) However, it later became clear that heavy nucleosynthesis cannot take place in the first minutes of expansion of the Universe and occurred at later stages where stars form. Chemical elements heavier than helium are produced in stellar interiors by thermonuclear synthesis.

Figure 12. G A Gamow (1904–1968).

Gamow argued that the detection of the primordial radiation cooled down to a temperature of 1–10 K according to his computations can be used as evidence of the singular beginning of expansion of the Universe. Gamow's prediction, which seemed to be fantastic and nonmeasurable, was confirmed in spurious observations of the radio sky, which were carried out by American radio physicists A Pensias and R Wilson [57] in 1965 with a quite different purpose. The temperature of the CMB was measured to be ~ 2.7 K, in full quantitative agreement with Gamow's prediction. Seven years before Pensias and Wilson's discovery, 3-K cosmic radio emission was really registered at the Pulkovo Observatory with a horn antenna constructed by Khaikin, Kaidanovskii, and Shmaonov [58]. But at that time, alas, those observations were unnoticed... .

After the discovery of the 3-K CMB, the model of the nonstationary, evolving Universe, expanding from the initial hot Big Bang stage, became the standard one. Thus did the second revolution in astronomy finished.

But it turned out that, in accordance with the words of a popular Soviet-era song, "There is the beginning of revolution but no end," already in the 1970s we were on the verge of the new third revolution in astronomy. This was related to the beginning of space research which, according to the felicitous remark by I S Shklovsky [59] and V L Ginzburg [60], imparted multiwavelength properties to astronomy.

13. Era of multiwavelength astronomy

On 4 October 1957, the USSR launched the first artificial Earth satellite. It now became possible for astronomers to bring telescopes beyond the atmosphere (which is opaque for most cosmic electromagnetic emissions). Before that, astronomical observations were carried out mostly in the optical range (where the wavelength changes about twofold), while space observations allowed probing the sky in a much wider range: gamma-rays, X-rays, ultraviolet, optical, infrared, and long-wavelength radio. Here, the emission wavelength changes from 10^{-8} cm (gamma-rays) to 10^{8} cm (long-wavelength radio), i.e., by 10^{16} times. This has made astronomical observations as reliable as physical laboratory experiments — despite the fact that astronomical objects are located at distances of several thousand, million, and billion light years.

In 1609–1610, Galileo observed the sky with the first telescope with a diameter of about 3 cm and 32-× angular amplification, which led to a breakthrough in the understanding of the surrounding world and observational grounds for the Copernican system. Presently, astronomers possess much more powerful observational facilities. Now, NASA/ESA Hubble Space Telescope, with a 2.4-m mirror, has been in orbit around Earth for more than two decades. Under operation are specialized space gamma-ray and X-ray observatories: NASA's Chandra and ESA's XMM-Newton (X-ray multimirror mission), international INTEGRAL, etc. In July 2011, a Russian space radiointerferometer, RadioAstron, was successfully launched. ESA's Planck space radio telescope explores CMB properties. There are now more than 12 ground-based large optical telescopes with mirrors 8–10 m in diameter. Multimirror 25–39-m ground-based telescopes will be constructed in the near future. Deep photometric and spectroscopic sky surveys are being carried out by automatic wide-field cameras (the Hubble Space Telescope, the Sloan Digital Sky Survey (SDSS), etc.). New, large automatic wide-field telescopes [e.g., the Large Synoptic Survey Telescope (LSST)] are under construction. The construction of the unique ALMA (Atacama Large Millimeter/submillimeter Array) ground-based radio interferometer working at short radio wavelengths is being completed. All these powerful observational facilities are engaged in solving problems of modern cosmology.

14. Discovery of CMB anisotropy

The maximum of the 3-K CMB spectrum falls around a wavelength of 1.3 mm. As the terrestrial atmosphere has poor transparency in this range, detailed spectral and anisotropy CMB studies are being carried out from space.

The first evidence of possible CMB anisotropy was obtained by a Russian specialized satellite, Relikt [61–63] in the 1980s. NASA's COBE (cosmic background explorer) [64] and WMAP (Wilkinson microwave background probe) [65] satellites proved the black-body character of the CMB spectrum and accurately revealed microwave radiation anisotropy at a level of $\Delta T/T \sim 10^{-5}$. The processing of the data obtained by the Planck satellite is now being completed.

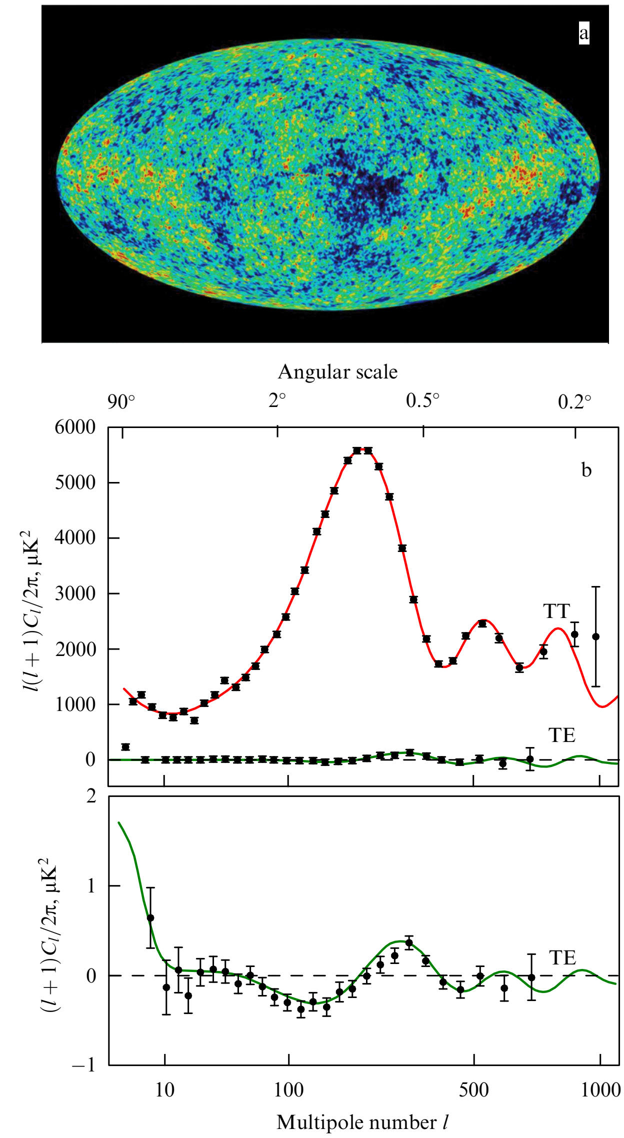

Figure 13. (a) Map of CMB fluctuations obtained by the WMAP satellite. (b) Position of the first maximum in the angular distribution of CMB fluctuations evidences the Euclidean type geometry of our three-dimensional space.

Ground-based radio and sub-mm observations on the South Pole Telescope and balloon CMB measurements turned out to be of great importance.

The map of CMB angular fluctuations (Fig. 13) corresponds to the age of the Universe of about 350 thousand years. At that epoch, radiation was separated from matter after hydrogen recombination, which occurred at a temperature of ~ 3000 K. The quantitative study of the fluctuations of the CMB intensity distribution allowed us to determine with good accuracy (of order a few percent) the basic parameters of the expanding Universe. In particular, it was definitely proved that our three-dimensional space is Euclidean and the mean density of all types of matter in the Universe is equal to the critical density $\rho_c = 3H^2/(8\pi G) \sim 10^{-29}$ g cm^{-3}.

15. Discovery of dark matter

In 1932, an American astronomer from Switzerland, Fritz Zwicky (1898–1974), who had been working in the USA since

1925, noted that, in addition to luminous galactic baryonic matter in the Universe, there must be invisible 'hidden' masses that manifest themselves only by its gravitation [66]. Zwicky studied a nearby galaxy cluster in Coma Berenices and discovered that galaxies in this cluster move with very high velocities of up to several thousand km per second. To maintain such rapidly moving galaxies in the volume of the cluster, a gravitational attraction is required that cannot be produced by only visible luminous masses in the galaxies. Zwicky estimated that additional masses 10 times as massive as the total visible mass of the cluster are needed. Later on, in the 1970s, astronomers from the USSR and USA discovered that the hidden masses (*dark matter*) must be present not only in galaxy clusters but also in isolated large galaxies. J Einasto [67], V Rubin et al. [68], J Ostriker and P Peebles [69], and their colleagues understood that dark matter forms invisible extended haloes around large galaxies. These haloes are quasispherical with radii 5–10 times as large as the sizes of the stellar systems themselves.

To date, there are at least 10 independent pieces of evidence of the existence of dark matter in the Universe. The most important of them include:

1. Motion of galaxies in clusters ($v \geqslant 1000$ km s^{-1}).
2. Rotation of galaxies (flat rotation curves).
3. Hot ($T \simeq 10^8$ K) gas in galaxy clusters (velocities of protons $v_{\rm p} \geqslant 1000$ km s^{-1}) (Fig. 14).
4. Gravitational lensing of light from distant galaxies in the gravitational field of closer galaxy clusters.
5. Motion of binary and multiple galaxies, etc.

Notably, each of these 10 independent bits of evidence for dark matter implies that the mass of dark matter is 5–10 times as high as that of visible baryonic matter. This looks like 10 independent lines intersecting in one point. So, the reality of dark matter prediction is very robust. However, as we mentioned in Section 7, there have been attempts to avoid introducing dark matter using modified gravitational theory, like MOND. We have already stressed that such attempts have so far been unsuccessful, since in this case one has to modify Newton's law of gravitation individually for each galaxy or galaxy cluster.

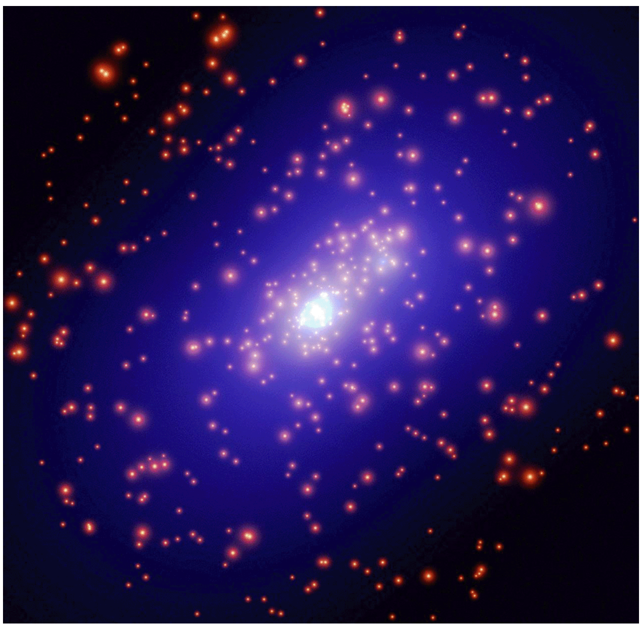

Figure 14. Hot gas ($T \approx 10^8$ K) concentrates at the center of a galaxy cluster evidencing the presence of dark matter which is 5–10 times as massive as the luminous baryonic matter.

16. Discovery of dark energy

In 1998–1999, two groups of astronomers discovered universal antigravity. Many scientists were involved in these studies (about 100 in total). One group was led by Brian Schmidt (Australia) and Adam Riess (USA), and another group was led by Saul Perlmutter (USA). The discovery was made using observational data of distant type Ia supernovae (thermonuclear explosion of a carbon–oxygen white dwarf with a mass close to the Chandrasekhar mass limit) [70–72]. The possibility of utilizing type Ia supernovae as 'standard candles' with known absolute luminosity in the maximum of the light curve was pointed out already in 1977 by Yurii Pskovsky (Sternberg State Astronomical Institute of Lomonosov Moscow State University) [73]. Due to their high luminosity, type Ia supernovae can be observed in the maximum light from very large distances (several billion light years), corresponding to redshift z on the order of unity and even larger than unity. At such huge distances, the motion (recession) of galaxies is determined by both their velocities and accelerations. By comparing the observed brightness of a type Ia supernova with the known absolute luminosity at the maximum, it is possible to determine the distance to its host galaxy. At small z (the case of nearby galaxies), the distance R is directly proportional to redshift z, and the brightness decreases as z^{-2} with increasing z. However, if z is not small, the distance–redshift relationship becomes more complicated: now it is dependent on both the recession velocity V and acceleration of recession of galaxies. Therefore, from a comparison of the observed brightness of type Ia supernovae at the maximum with the appropriate host galaxy redshift, one can infer the acceleration of recession. This acceleration was found to be positive, i.e., indeed the Universe is expanding with acceleration. Ordinary matter should decelerate expansion due to gravitational attraction between galaxies. The accelerating Universe implies the presence of a new type of matter (now referred to as *dark energy*). This matter effectively produces antigravity (i.e., gravitational repulsion), leading to acceleration of the Universe expansion. Presently, the accelerating expansion of the Universe is reliably established from observations of several hundred type Ia supernovae. In 2011, S Perlmutter, B Schmidt, and A Riess (Fig. 15) were awarded the Nobel Prize in Physics "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae."

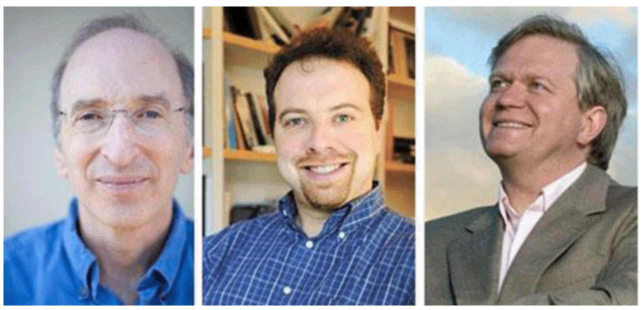

Figure 15. The discoverers of accelerating expansion of the Universe (from left to right): S Perlmutter, A Riess, B Schmidt.

The contribution of dark energy to the total energy budget of the Universe is estimated to be around 70%, i.e., the enigmatic dark energy actually now dominates in the Universe.

Besides the accelerating expansion of the Universe derived from observations of type Ia supernova explosions, there are at least three independent bits of evidence of dark energy.

(1) Evolution of galaxy clusters studied from observations of clusters at different z in X-rays [by the ROSAT (Röntgen) satellite, Chandra, XMM-Newton space observatories, etc.] and radio waves (using the Sunyaev–Zeldovich effect). The growth of galaxy clusters with time is determined by the action of two concurrent factors: the gravitational attraction of ordinary matter (baryons and dark matter), and the gravitational repulsion of dark energy. In order to obtain the observed dependence of the mass of a cluster on its redshift z, one should assume that the dark energy contributes $\approx 70\%$ to the total energy density in the Universe. Other values of the dark energy contribution would produce galaxy cluster characteristics contradicting observational data.

(2) The age of the oldest globular clusters ranges ~ 12–13 billion years. In old cosmological models which did not take into account Einstein's Λ term, the age of the Universe was about 11 billion years, which was less than the age of the oldest globular clusters.

This was worrying, so as early as the 1970s Ya B Zeldovich [74], I S Shklovsky [75], and N S Kardashev [76] suggested the employment of classical Lemaître's cosmological solution of GR equations with the Λ term to reconcile (enhance) the age of the Universe with that of the oldest globular clusters. Thus, the observed age of globular clusters is itself evidence of the presence of dark energy in the Universe.

(3) Precise measurements of CMB anisotropy, as mentioned in Section 14, allowed us to establish that our three-dimensional space is Euclidean, and the mean total density of all kinds of matter in the Universe (including dark energy) is equal to the critical value $\sim 10^{-29}$ g cm^{-3}. As the density of dark matter, baryons, and radiation is known from independent measurements, it is possible to independently estimate the dark energy density, which turns out to be $\sim 70\%$ of the total energy density in the Universe. This estimate coincides with the result obtained from type Ia observations.

An additional argument supporting the presence of dark energy follows from the treatment of kinematics of groups and clusters of galaxies carried out by A D Chernin and his colleagues [77] to explain the so-called Sandage paradox [78] which was formulated in 1972–1999. According to Alan Sandage, the regular cosmological expansion of the Universe with the 'standard' value of the Hubble constant (about $H = 70$ km s^{-1} per Mpc) is seen down to very small distances of 1.5–2 Mpc (5–7 mln light years), despite the fact that the size of the homogeneity cell in the Universe, as noted in Section 9, reaches about 300 mln light years, and there are strong inhomogeneities in matter density distribution on smaller scales. In spite of such inhomogeneities, the cosmological expansion is observed to be regular even on small scales and is indistinguishable from large-scale (of order a few thousand Mpc) expansion. How is it possible to understand this? Estimates of the dark energy density in six groups and clusters of galaxies made by A D Chernin and I D Karachentsev [77, 79] showed that local dark energy density is virtually coincident with that derived from the global expansion rate of the Universe. This may imply that the cosmological expansion on small scales is controlled by the dark energy antigravity.

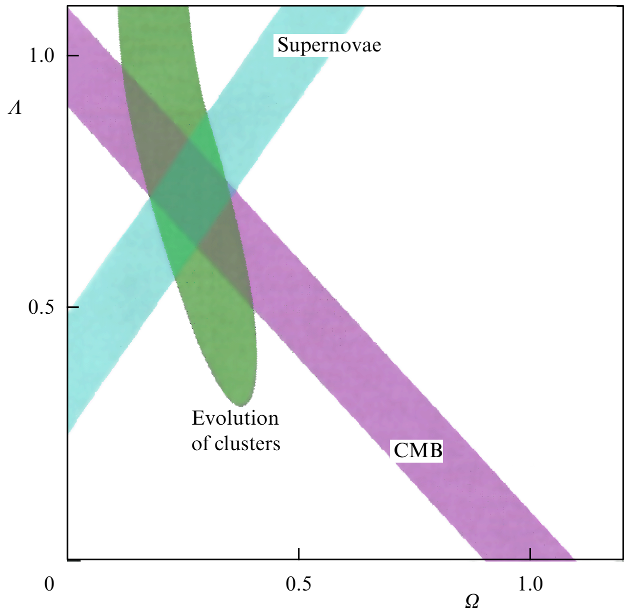

Figure 16. Determination of the dark energy density using observations in three different electromagnetic regions: radio (CMB), optical (type Ia supernovae), and X-rays (evolution of galaxy clusters).

Figure 16 illustrates three ways of determining the dark energy density based on observations made in different electromagnetic regions: X-ray, radio, and optical ones. The plot shows the results obtained from optical observations of type Ia supernovae (line *1*), radio studies of CMB fluctuations (line *2*), and observations of galaxy cluster evolution in X-rays (line *3*). It is seen that all three lines (bands) intersect in one region, corresponding to the dark energy Ω contribution of $\Lambda \sim 70\%$ and the fraction of the other matter reaching $\sim 30\%$.

17. New evidence of the real expansion of the Universe

The number density of relict photons decreases as the Universe expands. This means that the number density of photons (and their temperature) was larger in the past than now. From observations with 8–10-m telescopes, it was established that the population of excited levels of some extragalactic molecules at large distances is significantly higher than in the same molecules at small distances. Such low-lying molecular energy levels can be excited by CMB photons. This allows one to estimate the CMB photon number density in the past, which turned out to be higher. This fact, irrespective of the interpretation of the redshift in distant galaxy spectra, implies that the volume of the Universe increases with time, i.e., the Universe is really expanding.

18. Observations and modeling of the large-scale structure of the Universe

Deep photometric and spectroscopic sky surveys enable us to measure redshifts of many tens of thousands of galaxies and to construct the three-dimensional distribution of baryonic

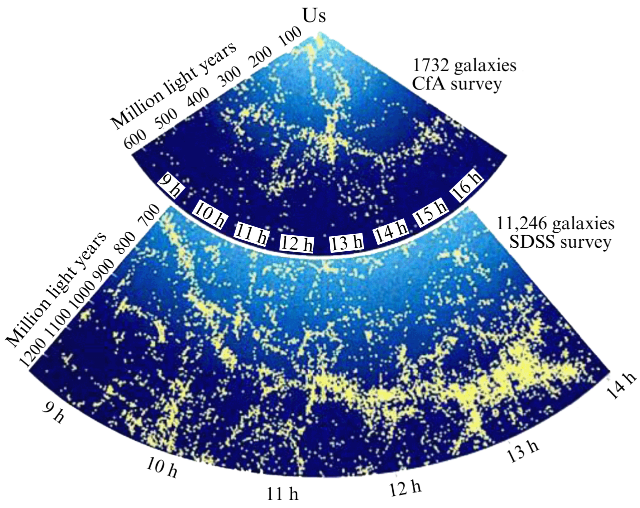

Figure 17. Three-dimensional map of baryonic matter distribution (galaxies and galaxy clusters) in the Universe based on deep photometric and spectroscopic sky surveys.

matter in the Universe (Fig. 17). This distribution was found to have a complex structure: galaxy clusters tend to form elongated structures (filaments), which look like large-scale structures in the Universe predicted by Ya B Zeldovich (so-called Zeldovich pancakes) [80] (Fig. 18). On the other hand, almost empty space regions (so-called voids) are found between the filaments. This structure was modelled using modern powerful supercomputers to be a result of the evolution of gravitational instability in the expanding Universe. The main factor controling large-scale structure formation was found to be not baryonic matter but the growth of inhomogeneities in dark matter distribution. Ordinary baryonic matter falls into the potential wells formed by dark matter (as a small addition to dark matter), thus forming the observed large-scale structure of the Universe.

Figure 18. Ya B Zeldovich (1914–1987).

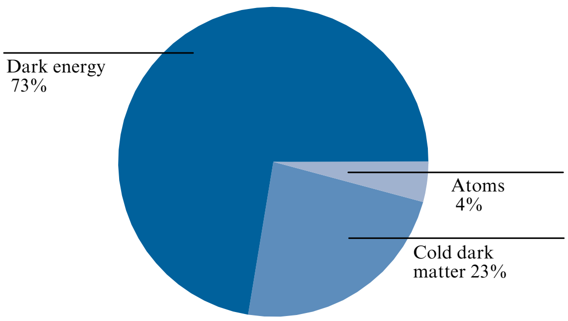

Figure 19. Energy content of the Universe.

19. Energy content of the Universe

Figure 19 presents the contribution of different types of matter in the Universe. Baryonic matter (atoms and molecules) contributes only $\sim 4\%$ to the total matter density.

The Universe is dominated by the so-called dark sector.

(1) *Dark matter* ($\sim 23\%$) does not emit and absorb photons, and only manifests itself by its gravitational attraction. It shows gravitational clustering and tends to concentrate around massive baryonic objects. Most likely it consists of special elementary particles which have not yet been discovered in nuclear accelerator experiments conducted in labs (there is hope to discover them using the Large Hadron Collider experiment at CERN, Geneva).

(2) *Dark energy* (73%) does not emit and absorb photons, either, and only manifests itself by its gravitational repulsion. Dark energy shows no gravitational clustering and most likely represents some field or a collection of fields. The dark energy density is virtually independent of time (redshift). That is why, the contribution of dark energy to the total balance of forces in the Universe increases with time as the Universe expands. When the age of the Universe was less than 7 billion years, the gravitational attraction of dark matter, baryons, and photons dominated dark energy repulsion. The contribution from dark energy became equal to that from ordinary matter, when the age of the Universe reached 7 bln years. For later epoches of Universe evolution (and its larger volume), the dark energy repulsion started dominating. That is why the Universe is accelerating now.

The dark energy pressure is negative: $p = -w\varepsilon$, where $\varepsilon = \rho c^2$ is the energy density, and w is the numerical coefficient close to unity according to modern astrophysical measurements: $w = 1.02 \pm 0.05$. As in GR cosmology, the source of gravity is $\rho + 3p/c^2$, and for negative pressure the source of gravity becomes negative (-2ρ). This leads to the fact that dark energy causes gravitational repulsion rather than gravitational attraction. The accurate measurement of the coefficient w in the dark energy equation of state is a major problem for modern observational cosmology, so that special space experiments are planned for its solving. The value of the coefficient $w = 1.02$ may suggest that dark energy represents a vacuum (for which w is precisely unity). A vacuum is a Lorentz-invariant medium, to which no reference frame can be attached: the vacuum density is strictly constant and similar in any frames. It should be noted that within present-day accuracy of measurements, w can be both lower than unity (so-called quintessence) and higher than unity (so-called phantom energy). Properties of quintessence and especially of phantom energy are very unusual; much theoretical speculation exists here.

It should be emphasized that there are models that explain the acceleration of the Universe expansion not by introducing a new type of matter like dark energy, but by modifying GR equations. For example, in so-called $F(R)$-gravitation, gravity is not connected with the curvature of spacetime (as in GR), but with a some function of the spacetime curvature.

20. Main evolutionary stages of the Universe

According to a very incisive phrase by I S Shklovskii [81], modern astronomy is multiwavelength and totally evolutionary. Therefore, the modern cosmological model is radically different from those of the World considered by our genial predecessors. First of all, modern cosmology takes into account all available observational data obtained by powerful modern facilities. The most important observations were described above. In particular, it is taken into account that conventional baryonic matter (stars, galaxies, as well as human beings) comprises only 4% of the total quantity of matter in the Universe, whereas most matter is in the dark sector (dark matter and dark energy) of an unknown nature so far. Cosmological models are constructed using the latest achievements of theoretical and experimental physics. But of particular value for us is that the modern model of the Universe is evolutionary: not only do we have grasp of the structure of the Universe, but we also know its evolution and even discuss its origin, as well as the possibility of the appearance of other universes which are not causally connected to our own. It is time to expand the Copernicus principle from Earth, the Sun, and our Galaxy to the entire Universe: apparently, our Universe is not a special case but is one of many causally disconnected worlds of the Multiverse. As noted above, our evolving Universe can be described using well-established physical laws starting at least from the epoch of primordial nucleosynthesis (mostly hydrogen and helium), i.e., from the first seconds and minutes after the singular state.

It is natural to ask the question: What did occur in the Universe before the primordial nucleosynthesis, i.e., at ages much less than one second? With some certainty we can state that expansion took place at these earlier stages, as well. But the further we go into the past, the less reliable our considerations become. When approaching the origin of the Universe, we have to deal with incredibly high temperatures and densities, where the physical laws known to us are not applicable any more. Therefore, when describing the very first stages of the formation of the Universe, researchers have to do huge extrapolations of the known laws of physics into the region where we generally have no objective grounds for their justification. Nevertheless, theories of the very early Universe have been developed in the last 25–30 years, which operate with colossal densities (for example, the Planck density reaches $\sim 10^{93}$ g cm^{-3}), extremely small time intervals ($\sim 10^{-43}$ s), and very tiny distances ($\sim 10^{-33}$ cm).

Inflationary theory provides an example. The theory is based on the original idea put forward more than 40 years ago by a physicist from St. Petersburg, E B Gliner (Fig. 20). According to Gliner's idea [82, 83], the initial acceleration of the Universe was produced by antigravitation of the primordial vacuum. This idea led to the elaboration of inflationary theories which consider different scalar fields and phase transitions in them. It has now been recognized that inhomogeneities in the matter density distribution, which were imprinted in CMB fluctuations and gave rise to the formation of galaxies and galaxy clusters, could be generated by quantum fluctuations of the primordial scalar field and a very rapid, exponential expansion of the scale factor in a new Universe being formed. The predicted spectrum of fluctuations (the scale dependence of the relative amplitude of fluctuations) is in agreement with CMB observations. Seminal work here was done by V F Mukhanov and G V Chibisov [84] of the Lebedev Physical Institute (LPI), RAS and by A A Starobinskii [85] (Landau Institute of Theoretical Physics, RAS).

Figure 20. Erast Borisovich Gliner. (San Francisco, 18 February 2013.)

Modern cosmology also solves the problem of the baryonic asymmetry of the Universe. For many years, it has been a mystery that we do not observe a lot of antimatter in the Universe, although in laboratory experiments a variety of particles and antiparticles are produced in nuclear reactions with equal probability. Here, the key ideas were put forward in the 1960–1970s by A D Sakharov [86] and V A Kuz'min [87]. Particle–antiparticle symmetry appeared to be not fully precise but slightly violated (*CP* violation). If baryonic charge is not conserved (i.e., a proton is unstable), in the extreme physical conditions of the early Universe due to the rapid expansion of the Universe (at the end of the inflationary stage), a weak asymmetry between particles and antiparticles can be sufficient to produce the observed baryonic asymmetry. Experiments show that the lifetime of a proton exceeds 10^{32} years, which is much longer than the age of the Universe (1.4×10^{10} years). Thus, although ways to solve the baryon asymmetry problem have been directed, it has not yet been solved. We should appreciate, however, the long proton lifetime... .

In this review, we do not aim to describe in detail all the problems of modern cosmology. The interested reader may refer to special monographs [1–3, 88]. Here, we will restrict ourselves only to a short enumeration of the main stages of the evolution of the Universe.

(1) *Quantum creation of a classical spacetime and the inflationary stage*. The time after the formation of the

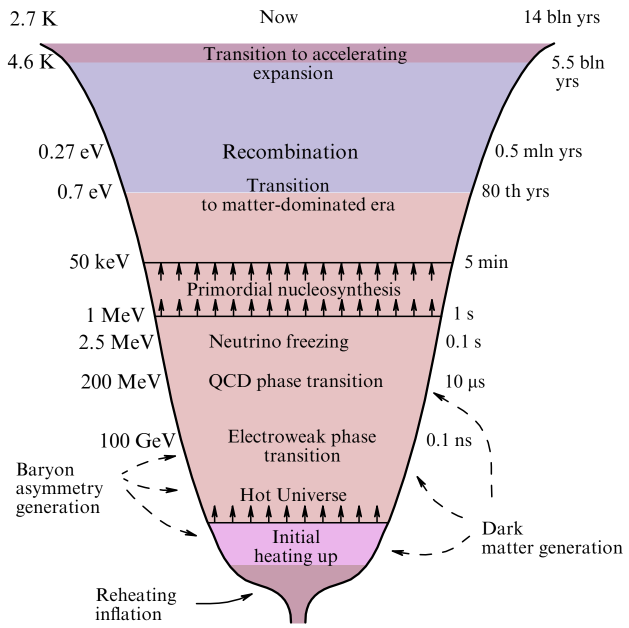

Figure 21. Main stages of the evolution of the Universe.

Universe, $t = 10^{-43} - 10^{-36}$ s. In this time interval, the scale factor of the Universe $a(t)$ increased exponentially by 10^{10^9} times. Papers by Sakharov [89], Lifshitz [90–92], Khalatnikov [90–92], Belinskii [92], Starobinsky [85, 93], Guth [94], Linde [95], Zeldovich [96–99], Rubakov [100, 101], Gliner [82, 83, 102, 103], Dymnikova [102, 103], Fomin [104], Grishchuk [105], Steinhardt [106], Mukahnov [84, 107], Chibisov [84], Sazhin [99, 100], Zelmanov [108], Lukash [109], and many others greatly contributed to the theory of the early Universe.

(2) *Decay of the scalar field, particle creation, entropy increase in the Universe, transition to the hot Universe with Friedmann expansion*, $t = 10^{-36}$ s (see, e.g., Rubakov [110], Starobinsky [111], Linde [111], Gorbunov [110], et al.).

(3) *Generation of baryon asymmetry*, $t = 10^{-35}$ s (see, e.g., Sakharov [112], Affleck [113], Dine [113], Kuz'min [87, 114], Rubakov and Shaposhnikov [114], et al.).

(4) *Electroweak transition and quantum chromodynamics phase transition, confinement of quarks*, $t = 10^{-10} - 10^{-4}$ s (Rubakov and Shaposhnikov [115]).

(5) *Freezing of neutrinos*, $t = 10^{-1}$ s.

(6) *Freezing of neutrons* $(n_n/n_p = 1/5)$, $t \simeq 1$ s.

(7) *Primordial nucleosynthesis*: H, ^{4}He, ^{3}He, D, T, Li, $t = 1 - 200$ s (Gamow [116], Schramm and Olive [117], Zeldovich [118], Varshalovich [119], et al.).

(8) *Dark matter domination*, $t =$ 60,000 years (Einasto [120], Zeldovich, Sunyaev [121], et al.).

(9) *Recombination and separation of radiation from matter*, $t =$ 350,000 years (Gamow [116], Peebles [122], Kurt [123], Sunyaev [123], Zeldovich [123], Doroshkevich [124], Novikov [124], et al.).

(10) *Dark ages*: H, ^{4}He, ^{3}He, D, T, Li, $t = 100 - 200$ mln years.

(11) *First stars* (IIId population) $(M = (100 - 1000)\, M_{\odot})$, $t = 200$ mln years (M Rees [125], et al.).

(12) *Large-scale structure formation*, $t \approx 1$ billion years (Lifshitz and Khalatnikov [90, 91], Sakharov [89], Zeldovich [126–129], Sunyaev [127], Shandarin [128, 129], Doroshkevich [130, 131], Einasto [120], Gurevich and Zybin [132, 133], Lukash [134, 135], et al.).

(13) *Transition to accelerating Universe*, $t = 7$ billion years (Perlmutter [72], Schmidt [71, 136], Riess [70], Starobinsky [137, 138], et al.).

(14) *Modern epoch*, $t = 13.7$ billion years.

Figure 21, borrowed from book [1], shows the main stages of the evolution of the Universe, including the moment of its transition from decelerating to accelerating expansion (at an age of $t = 7$ billion years).

21. Multiverse. Theory of eternal inflation by A Linde

Thus, at the very early stages of the formation of the Universe (10^{-43} s after the creation of classical spacetime) an inflationary expansion of the Universe apparently took place. In the period of time between 10^{-43} and 10^{-36} s, the Universe expanded exponentially. After that, the primordial scalar field decayed to produce a great amount of entropy and particles. There are two important observational facts supporting the existence of the inflationary stage: an (almost) Euclidean geometry of our 3D space as inferred from CMB fluctuation observations and an (almost) flat spectrum of small initial fluctuations existed immediately after the origin of the Universe (the so-called Harrison–Zeldovich spectrum), which follows from the analysis of modern observational data. An important clue could also be the detection of CMB polarization fluctuations produced by primordial gravitational waves. This is a major task of the Planck space mission.

A natural question arises: what was there before the formation of classical spacetime and the inflationary stage? According to current concepts, a quantum stage preceded inflation. Time intervals shorter than 10^{-43} s and distances smaller than 10^{-33} cm cannot be considered as continuous space and time. At huge energy density (10^{93} g cm^{-3}) of the scalar field (vacuumlike matter), space and time were disintegrated into individual quanta, and all that was in the state of a so-called 'boiling vacuum', as theorists say. Characteristics of space and time changed dramatically, including the dimension and topology of space. It is very difficult to study these processes, since so far we are not acquainted with the rigorous theory of quantum gravity. The unification of GR and quantum physics can be done within the framework of string theory or M-theory. Computer modeling has shown that, due to quantum fluctuations, the boiling vacuum can form separate 'bubbles' (expanding universes). Any such universe is similar to our own but can have different physical properties, different physical laws, and different physical constants (compared to our Universe). Some bubbles from the boiling vacuum can develop for an infinitely long time, while some will collapse to transit into a new physical state (Fig. 22).

Up to the end of the 20th century, we thought that the expanding relativistic Universe included the entire surrounding world. We called this world a unique term — the Universe. Since then, the picture of a unique possible world has changed, and now the picture of multiface universes — the Multiverse — is emerging. This signals the beginning of the third revolution in astronomy and cosmology.

Thus, the scenario of eternal inflation predicts the infinite creation of different casually disconnected worlds. This process has neither boundaries nor limits. According to the Copernican principle, as mentioned in Section 6, our Universe is one of many universes in the Multiverse.

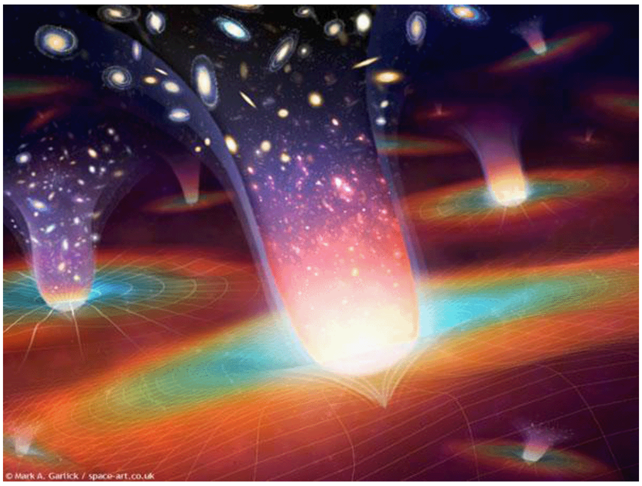

Figure 22. 'Boiling vacuum' and quantum formation of universes in the Multiverse.

One of the creators of the modern theory of the inflationary Universe, Andrey Linde (researcher at the Lebedev Physical Institute, professor at Stanford University), wrote that there is no end to the evolution of the Universe (Multiverse) [139].

It is not clear how to confirm from observations the described model of the Multiverse; however, we should note that the ways of testing the model do not seem to be hopeless: different universes can be connected by topological tunnels ('wormholes') which can be relics of the boiling vacuum stage. Due to inflationary expansion, such tunnels can be transformed from microscopic spacetime structures into macroscopic objects. These tunnels can be served to transport matter and information, including those from other universes. The search for wormholes in the Universe (entries to other universes) is a major issue in modern astrophysical observations. In Russia, I D Novikov, A A Shatsky, and N S Kardashev are actively involved in these studies [140, 141]. This issue is included in the observational program of the Russian RadioAstron space mission [142].

22. Anthropic principle

One of the first formulations of the anthropic principle was made in the middle of the 1930s by an outstanding cosmologist from the Sternberg Astronomical Institute of Moscow State University, Abraham Zelmanov (1913–1987) [143], and by the well-known theoretical astronomer, Gregory Idlis (1928–2010) [144]. Zelmanov argued that the observed Universe is as it is because other universes evolve without witnesses. This was said long before the Multiverse concept arose. Not all scientists take the anthropic principle seriously. The proponents of the anthropic principle draw attention to the fact that our Universe is well suited for life, including for human beings. Serious physical and astronomical arguments supporting this principle have been put forward by B Carter, I L Rozenthal, R Dicke, G Barrow, and others. The principal argument is that the set of physical constants and physical laws operating in our world provide good opportunity for the development of life. Of special importance is the fact that relatively small variations of physical constants could make the Universe unsuitable for life. In other words, our Universe is tuned very finely for the appearance of life.

Specialists distinguish strong and weak anthropic principles. The strong anthropic principle sounds severe: our Universe is specially formed such that we can naturally exist there. The strong anthropic principle releases our Universe from the action of the Copernican principle and makes our Universe unique. The weak anthropic principle is more 'democratic' in its sounding: it asserts that if there are many universes, then we are living in the one that is suitable for life. Other universes, according to A L Zelmanov, "can develop without witnesses," since physical constants and laws are unsuitable for life there.

The weak anthropic principle is in good agreement with the new concept of the Multiverse described in Section 21.

A detailed analysis of the fine tuning of our Universe for life was done, for example, in papers by I L Rozenthal. Here is one of his arguments [88]:

"In our opinion, the most striking example is provided by the instability of the Methagalaxy structure relative to the mass of the electron m_e. Indeed, a hydrogen atom in the Methagalaxy is absolutely stable. Its stability at sufficiently low temperatures ($T < m_e$) is guaranteed by the energy conservation law, which prohibits the reaction

$$\mathrm{P} + \mathrm{e}^- \to \mathrm{n} + \nu\,. \qquad (6.31)$$

To avoid the collapse of a hydrogen atom, the following condition must be fulfilled:

$$m_e < \Delta m_N = m_n - m_p \simeq 1.3 \text{ MeV}\,, \qquad (6.32)$$

where $m_{n,p}$ is the mass of a neutron or a proton, respectively. However, using the well-measured values of masses of particles participating in reaction (6.31), it is easy to see that if m_e were increased by more than 2.5 times, reaction (6.31) would occur at arbitrarily small temperatures. This would mean that with increasing m_e, a hydrogen atom would collapse to form a neutron and a neutrino."

Then I L Rozenthal stresses that at the stage of primordial nucleosynthesis in the Methagalaxy with heavy electrons, almost all matter in the Universe would be turned into neutrons and neutrinos, according to reaction (6.31). In such a universe, only neutron stars can exist, in whose interiors there are no thermonuclear reactions that are necessary to produce carbon, oxygen, silicon, and other heavy elements needed for life.

According to I L Rozenthal, the limits of possible variations of fundamental physical constants, within which the structure of our Universe does not change significantly, are very narrow. For example, the relative difference between the masses of the neutron and the proton, $m_n - m_p$, lies in the range (0.4, 1.6), and the admissible range for a relative change in the fine-structure constant $\alpha_{em} = e^2/\hbar c = 1/137$ covers (0.8, 1.6). The very high sensitivity of the parameters of our Universe to comparatively small variations of physical constants implies that different physical constants, and even different physical laws, can be found in different universes of the Multiverse. As noted above, the weak anthropic principle allows us to generalize the Copernican principle to the entire Universe: it is one of many equal universes in the Multiverse, except for having been randomly created at the quantum stage with a set of physical constant suitable for the origin of life. Possibly, in the Multiverse there are other causally disconnected universes, in some of which the set of physical constants and laws are unfavorable for life, and others where they are favorable for the appearance of life.

23. Conclusion

In this review, we discussed the development of our concepts about the structure and evolution of the Universe. Starting from the early naive concepts about the structure of the Universe (1000 BCE), our knowledge, guided by the desire to understand the nature of the surrounding world, has experienced two scientific revolutions: the Copernican one (the transition from geocentric to heliocentric world), and the Einstein–Friedmann–Hubble one (the transition from the static Universe to the expanding, evolving Universe). Now we are on the verge of the third revolution in astronomy (the discovery of accelerating expansion of the Universe and the recognizing of a small contribution from baryonic matter to the total energy density of the Universe).

Modern cosmology started in the first decades of the 20th century. Over almost 100 years since Slipher's first observations and the cosmological work by Einstein, cosmology has turned from abstract and sometimes seemingly fantastic considerations into a mature key natural science of the 21st century. Cosmology now stands on solid observational ground around which the theory is developing, based on modern achievements of physics, including general relativity, nuclear physics, and particle physics. The recent discovery of the Higgs boson at the Large Hadron Collider should be emphasized, which can stimulate new theoretical research on cosmology.

Cosmology poses new problems, puts forward new advanced ideas and concepts, makes challenging predictions and presents a rich picture of the surrounding world, which has already become an integral part of human culture. As in every complex and lively science, there are unsolved problems in cosmology, which actually stimulates further development of this fascinating science.

To conclude, we reproduce a deep exposure of the sky field in the direction of the galactic pole (in the Fornax constellation) obtained by the Hubble Space Telescope (Fig. 23). The sky field has an angular size of 2.5 arcminutes and was observed by the HST with a total exposure of about 2 mln seconds (≈ 0.8 months). The field has almost no stars from our Galaxy; all visible objects belong to our Universe. The faintest galaxies have a brightness of the 30th stellar magnitude. Their redshift is about 10, and their age is less than 500 mln years (cf. with the current age of the Universe being 13.7 bln years). The total number of galaxies in the deep HST field is about 6,000. This picture clearly demonstrates that our Universe is the realm of galaxies. Each galaxy contains from one to a few hundred billion stars. Almost each galaxy hosts in the center a supermassive black hole with a mass ranging from 10^6 to 10^{10} solar masses. In addition, there are stellar-mass $[M = (5-20)\,M_\odot]$ black holes in each galaxy, with a total mass of around 0.1% of the galaxy's baryonic mass (including stars, gas, and dust).

Figure 23. Ultradeep Hubble field observed by HST with an exposure of ≈ 2 mln s.

Future giant optical and infrared telescopes with 25–39 m mirrors and the forthcoming James Webbs Space Telescope with a 6.5-m mirror are intended to detect signs of the so-called Dark Ages of the Universe ($\sim$ 100–200 mln years), when the Universe was filled with only neutral hydrogen and helium and stars and galaxies have not been formed. Observational evidence for such a boundary of existence of luminous baryonic matter would additionally confirm our concepts of the structure and evolution of the Universe.

Note added in proof. After the present paper was submitted, new treated results of CMB observations by the Planck space observatory were published (arXiv:1303.507.6; 1303.508.2; 1303.508.3). These results basically confirmed the WMAP results. The new value of the present-day Hubble constant is $H_0 = 67.0 \pm 1.2$ km s^{-1} per Mpc, the appropriate age of the Universe is $T = 13.8\times\ 10^9$ years (cf. WMAP values of $H_0 = 70.2 \pm 2.2$ km s^{-1} per Mpc, and $T = 13.7 \times 10^9$ years). Small but significant deviations from the Harrison–Zeldovich flatted spectrum of primordial fluctuations have been found, which put additional bounds on the class of inflationary models.

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