HISTORICAL OVERVIEW OF THE UNIVERSE

Hartmut Schulz
Astronomical Institute, Ruhr University, D-44780 Bochum, Germany

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Contents

Summary

The core of this article consists of two parts. The first part (Section 2) outlines some major achievements in the history of astronomy that led to modern technology-based astronomy. The second part (Section 3) describes a scenario of the evolution of the Universe as it appeared plausible at the end of the twentieth century.

Summary of Section 2 (History of Astronomy):

Relatively complete historical records are available from the Greeks, who had already devised complicated schemes to describe the motions of the planets. Hipparchus was the great astronomer of the antique world and Ptolemy was outstanding in summarizing and reviewing the knowledge of his time. After the decay of the Roman empire, for many centuries astronomy only flourished in Arabian societies. In the sixteenth century, T. Brahe and his assistants reached the utmost precision possible in describing the observed positions of celestial objects in the pre-telescope era. This observational breakthrough helped to establish new concepts, which dethroned the Earth from its special central position in the world. Astronomical evidence had begun to put physics on firm new fundamentals (N. Copernicus, J. Kepler, G. Galilei, I. Newton), a process that was successfully continued in the seventeenth and eighteenth centuries.

In the nineteenth century, distances to nearby stars were measured, nebulae were catalogued, and the spectroscopic decomposition of light was learned as the first astrophysical method. In the twentieth century, stellar spectroscopy was developed as a way of determining stellar parameters, in particular the abundances of the chemical elements. Computer simulations of the evolution of stars provided the production rates of heavy elements, which are returned to the interstellar medium by stellar explosions and stellar winds. Galaxies were found to be “island universes.” It was recognized that they are generally receding from Earth in proportion to distance. At the same time, general relativistic world models predicting expanding space were appearing, and provided a natural framework for interpretation. Such world models should have a “hot past,” with radiation and other relativistic components dominating at early times and culminating in a singular beginning with a “hot big bang.” A faint cosmic background radiation was discovered in 1965, as had been predicted by the hot-big-bang scenario. Another triumph was the correct prediction of the cosmic helium abundance, which cannot be produced by nucleosynthesis inside stars.

One of the leading themes of the last three decades of the twentieth century was the nature of quasistellar objects and active galactic nuclei. These are explained by accretion disks, luminous whirlpools around supermassive black holes, situated in the centers of galaxies. Evidence for a million-mass black hole has been found in the center of the Galaxy. A second modern topic is the formation of galaxies. Deep observations suggest that the shapes and stellar populations of present-day galaxies were mostly due to a gradual process. Collisions and merging among early galaxies stimulated star formation, recycled the interstellar medium and rearranged angular momentum. To detect the first objects formed—which are presumably subgalactic—is a task for the twenty-first century.

Summary of Section 3 (A plausible history of the Universe):

Standard world models, extrapolated backwards in time, lead to a “hot big bang,” which is thought to mark the beginning of the Universe. Owing to the lack of a generally accepted theory of quantum gravity, this beginning cannot be approached closer than 10^{-43} seconds. At this moment, the temperature is estimated to be 10^{32} K. A “superforce” indistinguishably joins the four currently known forces of the Universe. Expansion of space lets the Universe cool, with the superforce breaking apart into different types of interactions, via stepwise phase transitions completed at 10^{-10} seconds (10^{15} K).

A far-reaching phase transition occurred once the strong interaction had been separated from the electroweak interaction at 10^{-36} seconds, corresponding to 10^{28} K. At this time, the Universe commences a brief phase of accelerated expansion, called Inflation, suddenly increasing the size of the volume of space by several tens of powers of ten (e.g. by 10^{50}). Quantum fluctuations originating in the inflation era are prime candidates for being the seeds of the structures that subsequently grow, eventually leading to the first objects and galaxies.

The light-element nucleosynthesis epoch began at one second (10^{10} K) when it became possible to unite neutrons and protons to form deuterium, the decisive ingredient to form the nuclei of helium-4, helium-3 and lithium-7 during the subsequent few minutes. The agreement of the measured and predicted abundances of these light elements is one of the strongest arguments backing the hot big bang theory.

The early Universe consisted of a tiny fraction of normal matter particles (baryons) plus a larger amount of gravity-contributing dark-matter particles embedded in a sea of photons: the radiation particles. The number ratio of baryons to photons of about one part in a billion stays constant in the expanding Universe. The fact that during expansion the energy density of matter is less strongly diluted than that of radiation leads to a cosmic epoch at which both energy densities are equal. Afterwards, matter dominates and radiation becomes unimportant as a source of gravity. Radiation is trapped by interaction with the electrically charged particles until, at several hundred thousand years after the big bang, the Universe has become sufficiently cold that electrons are caught by the atomic nuclei to form neutral atoms, mostly hydrogen and helium. Now matter and radiation can expand and cool separately.

In the meantime, the excess density contrast of the seed fluctuations has grown, in particular that in the dark matter component. Gravitational attraction makes the baryons fall into "dark matter halos"' in which the first objects and galaxies can be formed. This occurs about a billion years after the big bang. The newly formed stars in the first galaxies obtain their luminosity from nuclear fusion processes, thereby breeding heavy elements that become released via mass loss of red giants or in supernova explosions of the massive stars or binary systems. Numerous collisions among the first stellar systems trigger further star-formation processes and larger systems are built by the merging of smaller systems. After many billions of years the present zoo of galaxy types has been formed, in which collisions, merging, and star formation still occur, albeit at a much lower rate. During their formation, many stars acquired dusty gas disks around them, out of which planets condensed. At least one of these systems, formed nearly five billion years ago, contained a little planet—called Earth—with the right distance to its central star—called the Sun—to provide the right conditions for life to evolve.

1. Introduction to the Sciences of the Universe

Due to various widely differing opinions about the "Universe," we need first to demarcate the limits of this topic. To most people, the Universe embraces all of space and time and every object, i.e. ourselves, the Earth, the stars, the galaxies, clusters of galaxies, everything else that can be perceived with our senses and instruments, and more because we have not yet found any limits. In this sense there is only one Universe, the unity that encompasses everything or the world as a whole, about which we have only incomplete information. There exist various different conceptions of the Universe depending on society, religion, ideology, profession, knowledge, or imagination.

We here confine ourselves to a crude description of the scientific picture of the Universe as it appeared at the turn of the millennium. The science of the Universe as a whole is called cosmology, which draws on the knowledge of other branches of learning like astronomy and physics. Cosmology does not claim to possess final answers and may be better described as the study of models of the Universe or world models. Successful world models have to be in line with the available astronomical, physical, and other relevant scientific measurements and observations. A world model is subject to abandonment or adjustments if there is evidence failing to fit its predictions. Thus scientific cosmology appears as a process by which it is hoped to reach a steady improvement of our understanding of the Universe.

Astronomy deals with all celestial objects, i.e. everything that can be perceived from the sky. In the discipline of astrophysics, celestial objects are studied with methods borrowed from physics. In this sense, astrophysics can be considered as a sort of applied physics. However, since celestial objects exist in a wider variety than terrestrial objects, astrophysics has turned out to have an important role in testing and extending the fundamentals of physics.

Most astronomers are actually astrophysicists. There are only a few traditional subdisciplines of astronomy which may not belong to astrophysics, such as positional astronomy (astrometry). For instance, in the latter discipline special techniques had been developed long before instruments of laboratory physics were attached to telescopes or physical theories were applied to understand the composition of cosmic matter, as is typical in astrophysics.

Our historical survey is organized as follows. In Section 2 the major steps that led to the worldview of current astronomy and cosmology are outlined. Section 3 presents a model of the evolution of the Universe from the “beginning” through to the formation of the Earth.

2. History of Astronomy

2.1 Antique Astronomy

Owing to a lack of written testimony, we can only speculate about the very beginning of astronomical thinking. It is nevertheless plausible that the earliest conscious human beings were already wondering about the celestial objects. Myths arose by noting correlations between celestial and terrestrial events. The Sumerians and Chinese gave early descriptions of the heavens. Figures in the sky were recorded at least 2000 years BC. Some of these so-called constellations, like the scorpion or the lion, are still in use today, albeit only as landmarks for the naked-eye observer—no longer for professional use. The Egyptians used astronomical alignments for their pyramids and temples. Their farmers utilized the appearance of the star Sirius to determine the time for planting crops.

The Greeks did sophisticated cosmological modeling. Eudoxus of Cnidus (about 409–356 BC) built a scheme of 27 rotating spheres to explain the celestial motions: One sphere for the stars, six for the sun and moon, twenty for the planets. Calippus extended Eudoxus' scheme to 34 spheres. At about 350 BC, Aristotle (384–322 BC) supplemented these models with an additional 22 spheres. Aristotle summarized his view in treatises, which heavily influenced the "authorities of knowledge" in Europe for the next two thousand years.

For the next 500 years, the city of Alexandria became the "center of science." One of the great astronomers of that epoch was Aristarchus of Samos (310 to about 230 BC). Rather than putting the Earth into the center of the world, he already envisioned the Sun in the center coinciding with the center of the sphere of the fixed stars. This view was "more correct" than the "Earth-centered" standard world picture which would be believed until the fifteenth century.

Eratosthenes (276 BC to 195 or 196 BC), another distinguished member of the Alexandrine school, is famous for the impressively correct numbers he gave for the size of the Earth and the obliquity of the ecliptic. Hipparchus (about 190 to 125 BC) is commonly considered as the greatest astronomer of the ancient world. He founded the mathematical discipline named trigonometry. He systematically applied powerful geometrical schemes to represent celestial motions (eccentrics, i.e. circles with the center displaced from the observer, and epicycles, i.e. small circles whose center is orbiting along a larger circle). Moreover, Hipparchus was himself a careful astronomical observer who also made systematic but critical use of older observations to discover changes in the sky beyond those which could be detected during a human's lifetime.

The great unifying summary of Greek astronomy, later called the Almagest, was written by Claudius Ptolemaeus, known as Ptolemy (around 150 AD; almost nothing is known about his life). The Almagest consists of 13 books, which rely heavily on earlier work, in particular on that of Hipparchus who is abundantly quoted. It became the bible of astronomy for many centuries, a standard text in addition to the work of Aristotle to whom more philosophical competence was attributed. Ptolemy assumed an Earth which lies motionless in the center of the heavens. The Earth is a point in comparison with the distance of the fixed stars. The heavens are spherical and revolve like a sphere. From a present-day perspective, there is, in principle, no mistake in mathematically describing celestial motions by taking the position of the Earth as the zero point of the reference frame. However, it makes matters awfully complicated. Referring the motions of the planets to the Sun is the simpler choice, as J. Kepler, G. Galilei, and I. Newton recognized many centuries later. After Ptolemy, occasional writings but no truly original ideas are known from the Alexandrine school, which came to an end in AD 640 when Arabs captured the town.

2.2 The Middle Ages (600 to 1500)

In this era, no first-rate discovery was made in astronomy. After the decay of the Roman Empire, new political order structures based on the Christian religion were established in middle Europe, leading to continuous struggle that hampered scientific progress. However, in those parts of the Roman Empire conquered by Arabic peoples, older astronomical knowledge from the west as well as from the east was compiled, preserved, updated, and improved by new observations. The Arabic interest in astronomy was stimulated by practical religious applications (lunar calendar; direction to Mecca) and astrology, the belief in the possibility of predicting the future by means of the stars. Modern astronomers reject astrology, having no basis in physics, as a superstition.

Notable scholars of the Baghdad school who translated and improved the Almagest were Tabit ben Korra (836–901) and Abul Wafa (939 or 940–998). Important astronomical and mathematical tables, the Hakemite Tables, were generated by Ibn Yunos (?–1008) at Cairo, later revised under the superintendence of Nassir Eddin (1201–1273) at Meraga observatory (called the Ilkhanic Tables). Astonishingly precise tables were produced in Samarkand by Ulugh Begh (1394–1449). Arabic centers of education at Cordoba, Toledo, Seville, and Morocco had earlier led to the Toletan Tables in 1080 under the direction of Arzachel. After the victory of Spanish Christians, the Toletan Tables were superseded by the Alfonsine Tables in 1252, made by Jewish and Christian scholars under the general supervision of Alfonso X of Leon and Castile (1223–1284).

In the twelfth and thirteenth centuries, a series of scientific and philosophical treatises were translated from Arabic into Latin. Several universities were founded. Emperor Frederick II directed the translation of a number of Arabic books at Naples University (founded in 1224). In addition to preserving these fundamental works, original thinking also developed. A notable individual was Roger Bacon (1214–1294) who doubted much of the theses of Aristotle and had a fairly modern view in demanding controlled experiments combined with mathematical reasoning for scientific inquiries. In the fifteenth century, independent research by the flourishing Nürnberg school led to a mathematical revision of trigonometry, the issuing of almanacs for calendar purposes and, in particular, the “Ephemerides” which were designed to be useful for navigation at sea in the upcoming era of discovery by ocean voyages. The practical value of astronomy had become more significant.

2.3 The Evolution of Newtonian Physics (1500 to 1800)

The breakthrough in the understanding of the fundamental structure of the solar system (then believed to be a representative part of the world) is usually attributed to N. Copernicus (1473–1543). He proposed that the apparent motions of the celestial bodies are largely due to the motion of the Earth itself, thereby extending earlier speculations by the Pythagoreans, Aristarchus of Samos, Martianus Capella (fifth or sixth century AD) and others. By putting the Sun in the center of the world, he carried out the revolutionary, albeit conceptionally simplifying, step from Ptolemy’s and Aristotle’s geocentric view to a heliocentric universe. His great book *De Revolutionibus Orbium Celestium* appeared in 1543.

Only allowing for circular motions, the Copernican system still required epicycles (34 circles to describe the motions of the Moon, Earth, and five other planets) and appeared to be flawed in comparison with detailed observations. For the next revolutionary revision of the mathematical description, much improved observations were required. The most significant progress in observational astronomy was achieved by the Danish nobleman Tycho Brahe (1546–1601). After extensive studies and travels through Europe he observed a brilliant "new star" in the constellation Cassiopeia in 1572. He deduced that this object certainly had to be farther away than the moon and probably belonged to the fixed stars because it showed no sign of planetary motions. We now know that it was a "supernova," an exploding "fixed star" of which we still observe a remnant that is bright in X-rays and radio radiation.

Starting in 1576, Tycho built the most magnificent observatory of its time on the island of Hven, where he worked for twenty-one years with a number of assistants. With quadrants and clocks (telescopes were not yet available) he produced the most accurate stellar positions that had been made up to that time. The places of his nine fundamental stars differ from modern values by angles less than one minute of arc in most cases. He could not have done better because one minute of arc is about the resolution limit of the naked eye. By careful observation of the brilliant comet from 1577, Tycho was able to refute the then popular belief that comets are situated in the higher regions of the Earth's atmosphere. After the death of the king, Tycho lost support from the Danish court and left Hven in 1597. Following an invitation from the Emperor he settled in Prague in 1599 where, ten months before his death, Johannes Kepler (1571–1630) joined him as assistant.

Kepler became the successor of Tycho as mathematician to the Emperor in Prague in 1602. There he acquired control over Tycho's excellent observations, which he used for the next twenty-five years to improve the theory of the Solar System. His three Laws of Planetary Motions are most famous. After fitting Tycho's observations of Mars, he concluded that planetary orbits could be simply described by ellipses rather than by a complicated machinery of circles. The second and third laws give quantitative information about the orbital velocities of the planets.

The second law states that the line joining the Sun and a planet must sweep through equal areas in equal times. Thus, when a planet is closer to the Sun (the closest location is called the perihelion), it must be faster to sweep the same area with a shorter line. The slowest motion is reached in the aphelion, the farthest location from the Sun.

The third law states that the square of the period of a planet is proportional to the cube of the semimajor axis (half the longest dimension of the ellipse) of its orbit. This law is useful to obtain the relative sizes of the orbits of the planets just from period measurements. One needs only one orbital extent measured in absolute distance units, the others can be obtained from timing. Therefore, in later history, frequent attempts were made to obtain an absolute measurement of the distance between the Earth and Sun because this fixes the scales of the other orbits as well. For most planets the deviation from a circle (given by the eccentricity, a measure of the flatness of an ellipse) is small so that for rough estimates the semimajor axis can be taken as the radius of the orbit. Kepler discovered his law about orbital ellipses from Tycho's observations of Mars, which fortunately exhibits a relatively large eccentricity.

Kepler himself was already thinking about dynamic causes of his kinematic laws, but was not conclusive. Making new discoveries with one of the first telescopes in use and putting physics on firmer ground, Kepler's contemporary, Galileo Galilei (1564–1642), was particularly influential. He described the mountains and craters on the Moon and showed that the hazy appearance of the Milky Way and some other objects was due to the poor resolving power of the naked eye. Galileo discovered that small bodies revolved around Jupiter like a little planetary system of its own, thereby supporting the Copernican view. He observed the phases of Venus and argued that these are in accord with Copernican theory but at variance with Ptolemy's view. Despite the quality of his arguments, the Inquisition of the Roman Catholic Church later forced him to recant. Among Galileo's numerous other achievements are a clear statement of the principle of inertia, by which an undisturbed body stays at rest or in uniform motion. He failed in his explanation of the tides (which he defended too emphatically) by rejecting the influence of the Moon, which had been suggested by Kepler and others.

Due to the Earth's rotation, the positions of fixed stars in the sky depend on time. Therefore, time keeping has historically been a major theme in astronomy and astronomical navigation. Significant progress was achieved by C. Huygens (1629-1695), a skilful telescope maker, observer and designer of the first practically useful pendulum clocks (patented in 1657). A usable clock on a ship could have served in turn to determine the terrestrial longitude at sea. O. Roemer (1644–1710) checked whether observations of the Galilean moons of Jupiter could be a substitute for a clock. He accordingly found in 1675 that the intervals between successive eclipses of a moon regularly decreased when the Earth in its orbit was approaching Jupiter, while they increased when the Earth receded. He correctly attributed this to the finite velocity of light, which could be measured by such observations. The problem of building a chronometer that works properly on a ship for fast and reliable astronomical navigation was finally solved by J. Harrison (~1760–1765).

Isaac Newton (1642–1727) became the great unifier of the new cosmology and the new achievements in terrestrial physics. He brought the motion of a falling apple and the motion of celestial bodies together by the principle of a general force, called gravitation, that works as an attractive force between all (positive) masses. In the case of two spherical bodies, this force is inversely proportional to the square of the relative distance of their centers and directly proportional to the product of their masses. This formula could then be used to derive Kepler's laws, which thereby became more useful because they now contained the masses, the cause of the force. Thus the mass of the Sun can be obtained from the motion of the planets, and the mass of a planet can be derived from the motion of an orbiting moon or other satellite. With his fundamental book *Philosophia Naturalis Principia Mathematica*, Newton put the new physics on a firm footing. He devised the method of calculus and also contributed to the fundamentals of optics, e.g. by discovering the basis of spectral analysis via resolving a beam of white light into different colors with a prism. Taking up an idea of J. Gregory (1638–1675), he constructed a reflecting telescope in 1686.

The mathematics of gravitational astronomy (or analytical mechanics) was later developed to great sophistication by L. Euler (1707–1783), A.C. Clairaut (1713–1765), J. D‘Alembert (1717–1783), J.L. Lagrange (1736–1813), P.S. Laplace (1749–1827), and C.F. Gauß (1777–1855). Theory guided the history of the discovery of the planet Neptune (1846) and the first asteroids (Ceres in 1801). Since then, most practical computations of motions in the Solar system and of other celestial systems have been applications of Newton‘s theory. The scaling of the distances within the Solar System was precisely verified and the paths of space vehicles or of the Apollo astronauts completely relied on this theory. In addition, Newton‘s more general principles still dominate most applications of physics because they work with sufficient accuracy under a wide range of circumstances.

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Biographical Sketch

Hartmut Schulz was born in Kiel in Germany in 1948. In 1974 he acquired the academic degree 'Diplom-Physiker' at the University of Kiel where he also obtained a Doctorate degree in Astronomy in 1977. After a post-doc year in Kiel he worked as astrophysicist at the Max Planck Institute of Astronomy in Heidelberg during the erection of Calar Alto Observatory in Spain until 1983. Subsequently he taught and conducted research at the Planetarium of Wolfsburg and the Universities of Bonn, Tübingen and Bochum. In 1995 he obtained the 'Habilitation' in Bochum where he is still teaching as 'Privatdozent' (University lecturer). He carried out astronomical observations at various telescopes in South Africa, Spain, Chile and analyzed data from the Hubble Space Telescope and the Rosat x-Ray satellite. In 1990 and in 1997 he taught as Visiting Professor at Dartmouth College, New Hampshire. His research extends from topics like the mass distribution of white dwarf stars, radiation cones in active galactic nuclei, the nature of infrared galaxies to relativistic cosmology and is documented in over 80 original scientific articles and about the same number of science reports.