UNIVERSE, STRUCTURE OF THE

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ABSTRACT

At present the most plausible theory of the origin of the universe is that it formed from the explosion of an extremely hot and dense fireball several billion years ago. During the first few seconds after the Big Bang, the energy density was so great that only fundamental particles (leptons, quarks, gauge bosons) existed. As the universe cooled and expanded after the Big Bang, nuclei and atoms formed and condensed into galaxies and stars and systems of them. The fundamental particles and a wide range of gravitational aggregates of them constitute the small-scale and large-scale structure of the present universe. The current knowledge of the elements of the structure of the universe based on the standard Big Bang model and the standard model of fundamental particles is considered.

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INTRODUCTION

INTRODUCTION

Every culture, from the ancient tale-spinners of the Indus Valley to the modern technocrats of the Silicon Valley, has held its own unique view of the cosmos. Astronomy, the oldest science mainly based on observation , cannot be separated from physical law and mathematics. Big advances in space science and technology in this century have allowed astronomers to look both deeper into space and farther back in time, thereby discovering a close connection between particle physics and cosmology. The study of the creation, evolution, and structure of the universe has become a legitimate subject for astronomers, physicists, and mathematicians.

The article presents an outline of the current knowledge about the structure, more precisely the structural elements, of the universe from the point of view of the standard Big Bang model (dubbed macrocosmos) and the standard model of fundamental particles (dubbed microcosmos). In this regard an important point has to be made that the article does not consider the time dependent phenomena that ought to characterize the evolution of the universe but is focused on the structural elements of the universe as discovered by observation at the present stage of the evolution of the universe. One can ask the question of how it is possible to understand the universe on the basis of its structural elements? The ancient atomic philosophers may have answered: This objection is similar to that of someone saying, how can the entire poem of Homer, the Iliad, be composed of only 24 letters, those 24 letters of the Greek alphabet. Hidden in that thought is, that the richness of the poem is not compromised by the fact, that a method exists to ultimately trace them back to a few, very elementary and simple elements, such as the formal contents of the Greek language to the 24 characters, that are being referred to as the Greek alphabet. However, the degree of the current understanding of the structural elements of the universe (compared with the 24 letters of the Greek alphabet) reveals the fact, that the scientific establishment is still far away from understanding the beauty of the structure and evolution of the universe as a whole (compared with the Iliad).

The article is divided into six parts. The first three parts recount the development of macrophysical and microphysical knowledge from prehistory to the present. Part four is devoted to the elements of the standard model of fundamental interactions, namely the leptons, quarks, and gauge bosons. The fifth part discusses the structural elements of the universe, from the large-scale structure down to the stars. Finally, the sixth part emphasizes the importance of mathematics for the physics and astronomy of the structure of the universe.

1 STRUCTURE OF THE ANCIENT UNIVERSE

1.1 Prehistoric Astronomy

From half a millennium before 4000 BC, long barrows - elongated burial mounds of earth - were arranged so as to be aligned on the rising and setting of bright stars. In the middle of the third millennium this technique was transferred to circular grave architecture, the so-called round barrows, and in this form it lasted for well over a thousand years. Why this particular phase in prehistorical astronomical activity is so important is that it testifies to the marriage of astronomy with geometry. There is clear evidence that the Sun and the Moon were observed. Stonehenge, shown in Fig.1, is the most famous prehistoric megalith (standing-stone monument) in Europe and lies north of Salisbury, England. Stonehenge had an exceptionally long history of use as a religous center and is also believed to have functioned as an astronomical observatory.

FIGURE 1.

1.2 Egypt

Some concern with astronomy had already been shown in a cosmology associated with the rulers Seti I (r.c.1318-c.1304 BC) and Ramses IV (r.c.1166-c.1160 BC). The Egyptians had by then long been adept at measuring time and designing calendars, using simple astronomical techniques. They too aligned their buildings on the heavens. Some early Egyptian sources speak of a cult relating the Sun-god Re (represented in art with a man's body and a falcon's head surmounted by a solar disk) and an earlier creator-god Atum. The cult of Re-Atum was well established by the time of the first great pyramids, that is, about 2800 BC. At first this was centered mainly on a temple to the north of the old Egyptian capital of Memphis. The place was known by the Greeks as Heliopolis, 'City of the Sun', but by the Egyptians as On (located northeast of Cairo, Egypt). By historical times, the priests of Heliopolis had laid down a cosmogony that held Re-Atum to have generated himself out of Nun, the primordial ocean. His off-spring were the gods of air and moisture, and only after them, and as their off-spring, were Geb, the Earth god, and Nut, the sky goddess, created. The deities of Heliopolis, (the Great Ennead) were made up with Osiris, Seth, Isis, and Nephthys, the off-spring of Geb and Nut.

1.3 Mesopotamia

In the dynasty of Hammurabi (r.c.1792-c.1750 BC) in Babylonia not all gods can be identified with stars. The three highest - Anu, Enlil, and Ea - corresponded to the heavens, Earth, and water.

1.4   Indian and Persian Astronomy

The oldest of the Vedic writings in Hinduism, the Rigveda (dating from between 1500 and 500 BC), gives more than one account of the creation of the world (Fig.2). The main version

FIGURE 2.

is that the world was made by the gods, as a building of wood, with heaven and Earth somehow supported by posts. Later it is suggested that the world was created from the body of a primeval giant. This last idea gave rise to the principle, found in later Vedic literature, that the world is inhabited by a world soul. Various other cosmogonies followed, with the creation of the ocean sometimes being given precedence, and place being made for the creation of the Sun and the Moon. There is a certain circularity in it all, however, since heaven and Earth are generally regarded as the parents of the gods in general; and water was sometimes introduced into the parentage. The Vedic literature gives no clear indication that mathematical techniques for describing the motions of heavenly bodies were discussed in India before the 5th century BC.

1.5   The Puranas and the Brahmapaksa

Although influenced by texts going back to Vedic times, and by Iranian sources too, the Puranas are Sanskrit writings about primordial times with cosmological sections dating from the 4th to 16th centuries AD of the Christian era. The Puranas deal with five topics: the creation of the Universe; the destruction and re-creation of the Universe, including the history of humankind; the genealogy of the gods; the reigns of the Manur; and the history of the lunar and solar dynasties. The Earth is now represented as a flat circular disc, with a world-mountain, Meru, at its center. The Meru is anchored to the yasti, which symbolizes the axis of the universe. The mountain is surrounded by alternating rings of sea and land, so that there are seven continents and seven seas. Wheels are conceived to carry the celestial bodies, these turning around the star at the north pole by Brahma, using cords made of mind. This cosmology was taken over by Jainism, a monastic religion which like Buddhism denies the authority of the Veda, but from the 5th and 6th centuries onwards it was undermined by the influx of a new form of Greek cosmology, with pre-Ptolemaic roots. In short, Aristotelianism reached India (see North, 1995).

2   MACROCOSMOS: FROM ANAXIMANDER TO EINSTEIN

2.1   Greek and the Roman World

Anaximander of Miletus (c.610-545 BC) is said to have made a map of the inhabited world, and to have invented a cosmology that could explain the physical state of the Earth and its inhabitants. The infinite universe was said to be the source of an infinity of worlds, of which ours was but one, that separated off and gathered its parts together by their rotary motion. Masses of fire and air were supportedly sent outward and became the stars. The Earth was some

sort of floating circular disc, and the Sun and the Moon were ring-shaped bodies, surrounded by air. The Sun acted on water to produce animate beings, and people were descended from fish.

Anaximenes (c.545 BC) elaborates on Anaximander's ideas, and argues that air is the primeval infinite substance, from which bodies are produced by condensation and rarification, he produces logical arguments based on every day experience. Again he introduces rotary motions as the key to understanding how the heavenly bodies may be formed out of air and water.

Pythagoras of Samos (c.560-c.480 BC) took the cosmic ideas of Anaximander and Anaximenes one stage further, saying that the universe was produced by the heaven inhaling the infinite so as to form groups of numbers. The Pythagoreans proposed a geometrical model of the universe, involving a central fire around which the celestial bodies move in circles. The central fire was not the Sun, although the Earth was certainly of the character of a planet to it. To account for lunar eclipses, the Pythagoreans postulated a counter Earth.

The discovery that the Earth is a sphere was traditionally assigned to Parmenides of Elea (c.515-c.450 BC), who was also said to have discovered that the Moon is illuminated by the Sun. A generation later, Empedocles (c.484-c.424 BC) and Anaxagoras (c.500 BC) seem to have given a correct qualitative account of the reason for solar eclipses, namely the obscuration of the Sun's face by the intervening Moon.

The discovery of the sphericity of the Earth, and of the advantages of describing the heavens as spherical, captured the imagination of the Greeks of the time of Plato (c.428-c.347 BC) and Aristotle (384-322 BC), in the 4th century, and of one man particular: Eudoxus of Cnidus (c. 400-c.355 BC), who produced a very remarkable planetary theory based entirely on spherical motions.

2.2   Aristotle's Universe

At the time of the Greek philosopher and naturalist Aristotle (384-322 BC), the Earth and the universe were seen as constructed out of five basic elements: earth, water, air, fire, and ether. The natural place of the motionless Earth was at the centre of that universe. The stars in the heavens were made up of an indestructible substance called ether (aether) and were considered as eternal and unchanging. Aristotle's cosmology was the first 'steady state' universe. The other basic elements - water, air, fire - were earthly elements. The celestial bodies, including the Sun, the planets, and the stars, were considered to be attached to rigid, crystalline spheres, which were supposed to revolve in perfect circles about the Earth. The three innermost spheres, closest to the Earth, contained water, air, and fire, respectively. The Egyptian-Greek astronomer Ptolemy (c.100-170 AD) left the Earth to be located at the centre of the universe but ascribed to the Sun and the planets a new place within the cosmological views of his time. The Sun and the planets would revolve in small circles whose centers revolve in large circles about the Earth ("epicycles"). The element of perfection and beauty ascribed to the divine heavens remained the circle out of which the orbits of heavenly bodies were composed. Basically, Ptolemaic ideas were devised to accomodate astronomical observations

of planetary motions. His "Almagest" described the motions of the heavens on this geocentric basis, employing wheels within wheels (epicycles) to obtain a plausible match with observations. Ptolemy's geocentric system dominated western thought on astronomy (including cosmology) until the time of Copernicus, fourteen centuries later (Fig.3).

FIGURE 3.

Eratosthenes (c.270-c.190 BC) was the first to accurately measure the radius of the Earth in 196 BC by determining the minimum angle between the Sun's direction and the vertical at Alexandria on the day of the summer solstice. He knew that a zero angle occurs approximately when the Sun was at its highest point at the city of Syene (now Aswan), and he knew the base of the triangle, i.e. the distance from Alexandria to Syene.

2.3   Copernicus' Universe

Copernicus (1473-1543), a Polish astronomer, placed the Sun at the center of the solar system with the Earth orbiting around the Sun, thus proposing a heliocentric cosmology (De revolutionibus orbium coelestium, 1543). This entirely new basis of cosmological consideration did not fit the observations much better than the Aristotelian-Ptolemaic system but was justified by the "divine" principle of simplicity in comparison to the rather complicated construction using epicycles as employed in Ptolemy's cosmology. However, like Aristotle and Ptolemy, Copernicus retained the conventional idea that the planets moved in perfectly circular orbits and continued to believe that the stars were fixed and unchanging. Kepler (1571-1630), a German astronomer and physicist, adopted the Copernician system but introduced the concept of planets with elliptical orbits. He still believed that the Sun was the centre of the universe. The cosmologies of Aristotle and Ptolemy had nevertheless been abandoned.

2.4   Newtons' Universe

The Italian philosopher Bruno (1548-1600) laid the groundwork for Newtonian cosmology by emphasizing that the universe is infinite and stars are scattered outward through infinite space (see, however, Fig.4). Bruno even went so far as to say that stars are Suns, perhaps with

FIGURE 4.

orbiting planets and life on them ("De l'infinito, universo e mondi", 1584). This far-reaching statement signaled a transfer of attention away from the planets in the solar system to the stars in the Milky Way. The laws describing the behavior of planets are the same laws which describe the behavior of the stars. That the physical laws are of universal nature, and can be applied on Earth as well as in the heavens, was discussed on a philosophical basis by the French philosopher and mathematician Descartes (1596-1650). He compared the universe with a giant clock, obeying mechanical laws which later on had a major influence on Newton's (1643-1727) thinking. It was his belief that the universe was infinite and that the primary qualities of the universe were mathematical in nature.

A major step in observational techniques was achieved through the invention of the reflecting telescope between, say, 1545 and 1559 by the Britain Leonhard Digges (c.1520-1559). But it was not until 1609 that the Italian astronomer and physicist Galileo (1564-1642) realized observationally that the Milky Way is actually a collection of individual stars. Galileo also observed mountains on the Moon and discovered four satellites around Jupiter. He had taken the first step toward deducing the structure of the Milky Way. The discovery of heavenly bodies that evidently did not circle the Earth, and his support for the Copernician heliocentric cosmology were described in his work "Dialogo sopra i due massimi sistemi del mondo, Tolemaico e Copernicano" (1632).

Cassini (1625-1712), an Italian-French astronomer, used the telescope to make accurate measurements of the "dimensions of the universe", particularly determining the distance of the Earth from the planet Mars. A rigorous mathematical foundation of Descartes' notion of the universe as a giant mechanical clock was provided by Newton's theory of gravity and his laws of motion ("Philosophiae naturalis principia mathematica", 1687). From these he explained Galileo's results on falling bodies, Kepler's three laws of planetary motion and the motion of the Moon, Earth and tides. Newton clearly realized that gravity is the dominant force for understanding the structure of the universe; however, he argued that the universe must be static in a famous letter he sent to the theologian Richard Bentley (1662-1742) in 1692. Mainly for religious reasons, at this time, constancy and stability were associated with the perfection of God and change with friction and decay. Philosophical and religious ideas served as the scaffolding upon which scientific systems of thought developed. It was Bentley who derived for the first time, based on Newton's gravitational theory, what is still considered to be one of the fundamental constants of nature, the gravitational constant.

In Kant's (1724-1804) cosmology the gravitational attraction of stars for each other was exactly balanced by the orbital motions of the stars and he argued that forces can act at a distance without the necessity for a transmitting medium. In 1755 Kant proposed the nebular hypothesis for the formation of the solar system. In 1788 Laplace (1749-1827) attempted a mathematical proof of the stability of the solar system (Système du monde, 1796). Stability and order of the universe were considered as eternal principles in the heavens and on Earth. The cosmology of Copernicus, as refined by Kepler, is now believed to be essentially correct.

2.5   Einstein's Universe

In 1915 Einstein (1879-1955) put forth his general relativity theory (a new theory of gravity); he applied this theory to cosmology in 1917. The theory describes gravity as a distortion of the geometry of space and time. Unlike Newton's theory of gravity, general relativity was consistent with special relativity, which Einstein had introduced in 1905. Cosmology, based on general relativity, broadened the problem into one of finding a model of the space-time structure of the universe. Einstein's original solutions of his gravitational field equations left the universe in a stable state of static equilibrium and he provided physical conditions required to maintain such static (time-independent) equilibrium (the "cosmological constant"). Only in 1922 Friedmann (1888-1925) succeeded in finding solutions of Einstein's field equations that evolved in time describing an expanding (or contracting, if one cares to reverse the sense of time) universe.

Persuasive observational evidence that the universe is indeed expanding and changing in time was found by Hubble (1889-1953) in 1929 while employing the technique known as Doppler shift for measuring the red shift of colors in the spectrum of nebulae. "Modern cosmology" may be said to have began with Einstein (1917) and Friedmann (1922, 1924), based on observations of cosmological relevance made by Slipher (1875-1969) in 1914 and Hubble in 1929. Slipher discovered the redshift of nebulae, later on identified by Hubble to be entire galaxies similar to the Milky Way; however, until 1929 their cosmological significance remained obscure. In 1929 Hubble had counted a great number of galaxies (to determine their distribution throughout the observable universe), and plotted the galaxie's redshifts against magnitudes for the brightest E-type cluster galaxies (Hubble diagram). Hubble found evidence that the outward speed of a galaxy is directly proportional to its distance away from the observer (Hubble law). This observational fact was exactly what would be expected if the universe is expanding, as discussed in a paper of Lemaître (1894-1966) in 1927. Hubble's diagram reveals a linear increase of the magnitude of galaxies with increasing redshift. In 1956, Hoyle and Sandage developed the q_0 criterion which could be used to distinguish one cosmological model from others. Lemaître's model and Hoyle's 'steady state' model were ruled out by predicting $q_0 = -1$, whereas Hubble's linearity gave $q_0 = +1$. Cosmology focused on the search for two numbers: H_0, the rate of expansion of the universe at the position of the Milky Way; and q_0, the deceleration parameter, characterizing the change of the rate of universal expansion. The value of q_0 is believed to lie in the range between 0 and 0.5; the value of H_0 is thought to be uncertain by a factor of about 2 ($H_0 = 100 h km \ sec^{-1} Mpc^{-1}$, where $0.5 \leq h \leq 1$). Theoretical ideas on which Big Bang cosmology is based were contained in the publications of Friedmann and Lemaître by 1930 (for an in-depth review see North, 1965).

2.6   Big Bang

Astrophysical arguments were introduced into the cosmological models with Gamow's (1946) prediction that helium (and possibly heavier elements) were generated at an early stage of the evolution of the universe. At this time it was believed that the relative abundance of cosmic nuclei represents truly cosmic abundances. Based on Gamow's arguments the cosmological criterion of the origin of chemical elements in the primeval fireball was substantiated by Alpher and Herman (1949, 1950) and Alpher et al. (1953). However, after Burbidge et al. (1957) it became evident that the bulk of the chemical elements beyond helium where not synthesized at the early stages of the expansion of the universe but in the stars. Only the synthesis of helium (Hoyle and Tayler, 1964), which is not produced in sufficient quantities in stars, and deuterium (Peebles, 1966), which is destroyed during galactic evolution, continued to need Gamow's primordial nucleosynthesis to arrive at reasonable abundances as observed in the universe. Later on Wagoner et al. (1967) were able to show that in addition to D, ^3He, and ^4He, the only other cosmologically significant element was ^7Li. In 1965 the microwave background radiation of 3 degrees Kelvin was discovered by Penzias and Wilson (1965), as predicted by Alpher and Herman in 1949 based on Gamow's considerations of a hot and dense origin of the universe.

Today the Big Bang cosmological model, the temperature of the microwave background

radiation, the abundances of D, ^3He, ^4He, ^7Li, and the astrophysically observed average density of galactic material are starting points for developments in cosmology.

2.7 Beyond the Big Bang

In the Big Bang cosmology, the universe has been expanding throughout its history. Mathematical calculations would suggest that the temperature and the density were infinite at the instant of the Big Bang. The universe is supposed to originate in the Big Bang, but the mathematical and physical structure of the model does not permit matter to originate. Additionally, the Big Bang model leaves unanswered several important questions regarding (i) the number of protons and neutrons in the universe, relative to the number of photons, (ii) the large-scale homogeneity of the observed universe, (iii) the actual density of the universe which is close to the critical density, and (iv) the origin of density perturbations from which small-scale (stars and systems of them) and large-scale (galaxies and systems of them) inhomogeneities have been developed (Kolb and Turner, 1990).

A new approach to explaining some of the questions left over by Big Bang cosmology began with Guth's (1981) paper inventing an "inflationary" period in the evolution of the universe. The phase transition associated with the break-up of the unified force in the Grand Unification epoch could leave the universe in a state of false vacuum, in which the vacuum has a very high energy density. This vacuum energy density acts like a cosmic repulsion and the universe embarks on an exponential expansion which "inflates" the universe by a factor of 10^{30} in a brief instant of time. This inflationary period ends when the vacuum energy density transforms into matter and radiation and the expansion of the universe continues. Besides offering explanation of the four questions above, it makes one concrete prediction: The present universal expansion should exhibit flatness to the extent of $\Omega_0 = 1 \pm \epsilon$ with $\epsilon < 10^{-6}$, if inflation was sufficient to extend to a distant $\geq cH_0^{-1}$ today. Observations of the luminous matter content of the universe reveal only $\Omega_0 < 0.002$, and the quantity of dark or non-baryonic material necessary to explain the flat rotation curves of spiral galaxies and the virial equilibrium of large groups and clusters of galaxies requires at most $\Omega_0 \approx 0.2$. The only way that $\Omega_0 = 1$ from inflationary cosmological models can be reconciled with observation is by the existence of non-baryonic weakly interacting particles. The unknown nature of dark matter led to considerable activities in fundamental particle physics to speculate about new basic constituents of matter. Additionally, the inflationary universe picture has stimulated far-reaching speculation about the ultimate origin of the universe.

Cosmology based on general relativity has thus moved close to fundamental particle physics based on quantum field theory. A new challenge emerged for physical theory and observation subsumed under the term 'quantum gravity'. Interaction between mathematics and physics, as exemplified by the role of Riemannian geometry in general relativity and functional analysis in quantum mechanics, became lively again. Cosmology is currently based on the two fundamental theories in twentieth-century physics, general relativity and quantum field theory. General relativity describes the gravitational force on an astronomical scale, while quantum field theory describes the weak, electromagnetic, and strong interaction of fundamental particles. A formal quantization of general relativity leads to unphysical infinities; encompassing gravity in

quantum field theories leads to a new connection of theoretical physics to modern mathematics, called string theory. However, there is still no quantum cosmology. Particularly, an inflationary era may have taken place in the early universe, but there is no proof that it did so (Manin, 1981; Schmid, 1992).

3 MICROCOSMOS: FROM LEUKIPPUS TO YUKAWA

3.1 Atomism

With regard to the structure of the universe, the belief persists, that certain objects are fundamental and that others are derived, in the sense that the latter are composed of the former. In one version of this distinction, the fundamental objects are particles, or points of matter. Although the view of which objects qualify as fundamental particles has changed many times, the notion that the universe is ultimately made of such material points, moving through space, has endured in some form ever since the theory of atomism was first proposed by the Greeks Leucippus (5th century BC) and Democritus (c.460-c.370 BC) in the 5th century BC (Whittaker, 1951 and 1953/1989).

An atom is the smallest unit of matter that is recognizable as a chemical element. Atoms of different elements may also combine into systems called molecules, which are the smallest units of chemical compounds (Fig.5). In all these processes, atoms may be considered as the ancient Greeks imagined them to be: The ultimate building blocks of matter. When stronger forces are applied to atoms, however, the atoms may break up into smaller parts. Thus atoms are actually composites and not units, and have a complex inner structure of their own.

FIGURE 5.

The first recorded speculations that matter consisted of atoms are found in the works of Leucippus and Democritus. The essence of their views is that all phenomena are to be understood in terms of the motions, through empty space, of a large number of tiny and indivisible bodies. The name "atom" comes from the Greek word "atomos", for "indivisible". According to Democritus, these bodies differ from one another in shape and size, and the observed variety of substances derives from these differences in the atoms composing them.

Greek atomic theory was not an attempt to account for specific details of physical phenomena. It was instead a philosophical response to the question of how change can occur in nature. Little effort was made to make atomic theory quantitative - that is, to develop it as a physical theory for the study of matter. Greek atomism, however, did introduce the valuable concept that the nature of everyday things was to be understood in terms of an invisible substructure of objects with unfamiliar properties. Democritus stated this especially clearly in one of the few sayings of his that has been preserved: "color exists by convention, sweet by convention, bitter by convention, in reality nothing exists but atoms and the void."

Although adopted and extended by such later ancient thinkers as Epicurus (341-270 BC) and Lucretius (c.95-55 BC), Greek atomic theory had strong competition from other views of the nature of matter. One such view was the four-element theory of Empedocles. These alternative views, championed by Aristotle among others, were also motivated more by a desire to answer philosophical questions than by a wish to explain scientific phenomena.

3.2 Atom

The atomic theory languished until the 18th and early 19th centuries, when physicists and chemists revived it to explain the properties of gases and some of the facts of chemistry. In these theories the fundamental particles, the atoms, remained indivisible points. The discovery in the late 19th and the 20th centuries that atoms were composite, rather than indivisible, set the stage for modern discoveries about fundamental particles (Pais, 1986; Whittaker, 1951 and 1953/1989).

When interest in science revived in Europe in the 16th and 17th centuries, enough was known about Greek atomism to form the basis for further thought. Among those who revived the atomic theory were Pierre Gassendi (1592-1655), Robert Boyle (1627-1691), and especially Isaac Newton. The latter part of Newton's book "Optics" is a series of detailed speculations on the atomic nature of matter and light, indicating how some of matter's properties are to be understood in terms of atoms.

In the 19th century, two independent lines of reasoning strengthened the belief in the atomic theory. Both approaches also began to reveal some quantitative properties of atoms. One approach, pioneered by John Dalton (1766-1844), involved chemical phenomena. The other, involving the behavior of gases, was carried out by physicists such as Rudolf Clausius (1822-1888) and James Clerk Maxwell (1831-1879).

Dalton's main step forward was his introduction of atomic weights. Dalton studied the elements then known and analyzed the data of their reactions with one another. He discovered the law of multiple proportions, which states that when several distinct reactions take place among the same elements, the quantities that enter the reactions are always in the proportions of simple integers - that is, 1 to 1, 2 to 1, 2 to 3, and so on. From this came the concept that such reacting quantities contain equal numbers of atoms and are therefore proportional to the masses of individual atoms. Dalton gave the lightest known element, hydrogen, an atomic weight of 1, and developed comparative atomic weights for the other known elements accordingly.

The study of gases in terms of atomic theory was begun by Daniel Bernoulli (1700-1782) in the 18th century. Bernoulli showed that the pressure exerted by a gas came about as the result of collisions of the atoms of the gas with the walls of its container. In 1811, Amedeo Avogadro (1776-1856) suggested that equal volumes of different gases, under the same conditions of pressure and temperature, contain equal numbers of atoms. Avogadro himself never estimated the magnitude of this value, although it is now known as the Avogadro number.

3.3   Electron

The history of particle physics has gone through four stages. In the first stage, Joseph J. Thomson (1856-1940) discovered (1897), by studying electricity passing through gases, that all atoms contain certain particles, called electrons, that carry a negative electric charge. Because atoms are electrically neutral, there must be balancing positive charges somewhere in the atom. Ernest Rutherford (1871-1937) proposed (1911), based on a series of experiments by Hans Geiger (1882-1945) and Ernest Marsden (1889-1970) that these positive charges are concentrated in a very small volume, called the atomic nucleus, at the center of the atom.

By the end of the 19th century almost all scientists had become convinced of the truth of the atomic theory. By that time, however, evidence was just beginning to accumulate that atoms are not in fact the indivisible particles suggested by their name. One source of such evidence came from studies using gas discharge tubes. In such tubes, a gas at low pressure is subjected to intense electrical forces. Under these conditions, various colored glows are observed to traverse the tube. One blue glow at one end of the tube, around the electrode known as the cathode, was observed for a wide variety of gases. The glow was shown by Joseph Thomson in 1897 to involve a stream of negatively charged particles with a charge-to-mass ratio, indicating the existence of a particle with a very small mass on the atomic scale. These particles were called electrons, and they were soon recognized to be a constituent of all atoms. That is, atoms are not indivisible but contain parts.

In the late 19th and the early 20th century it was also found that some kinds of atoms are not stable. Instead they transform spontaneously into other kinds of atoms. For example, uranium atoms slowly change into lighter thorium atoms, which themselves change into still lighter atoms, eventually ending up as stable atoms of lead. These transformations, first observed by Antoine Henri Becquerel (1852-1908), came to be known as radioactivity, because the atomic changes were accompanied by the emission of several types of radiation.

Atoms are ordinarily electrically neutral. Therefore the negative charge of the electrons in an atom must be balanced by a corresponding positive charge. Because the electrons have so little mass, the positive constituents of an atom must also carry most of the atom's mass. The obvious question arose as to how these varied parts are arranged within an atom. The question was answered in 1911 through the work of Ernest Rutherford and his collaborators. In their experiments they passed alpha particles - a type of radiation emitted in some radioactive decays - through thin gold foils. They observed that in some instances the alpha particles emerged in the opposite direction from their initial path. This suggested a collision with a heavy object within the atoms of the gold. Because electrons are not massive enough to produce such large deflections, the positive charges must be involved. Analyzing the data, Rutherford showed that the positive charge in an atom must be concentrated in a very small volume with a radius less than 10^{-12} cm, or one ten-thousandth the size of the whole atom. This part of the atom was called the nucleus.

3.4 Atomic Nucleus and Photon

Rutherford proposed an atomic model in which the atom was held together by electrical attraction between the nucleus and the electrons. In this model the electrons traveled in relatively distant orbits around the nucleus. The model eventually proved successful in explaining most of the phenomena of chemistry and everyday physics. Subsequent studies of the atom divided into investigations of the electronic parts of the atom, which came to be known as atomic physics, and investigations of the nucleus itself, which came to be known as nuclear physics. This division was natural, because of the immense difference in size between the nucleus and the electron orbits and the much greater energy needed to produce nuclear as compared to electronic changes.

The Rutherford model of the atom, however, had to face two immediate problems. One was to account for the fact that different atoms of the same element behaved in physically and chemically similar ways. According to the Rutherford model, electrons could move in any of the infinite number of orbits allowed by Newtonian physics. If that were so, different atoms of the same element could behave quite differently. This is actually a problem for any atomic model based on Newtonian physics, and it had already been recognized by Maxwell in 1870. The other problem was that, according to the principles of electromagnetism, electrons should continuously emit radiation as they orbit in an atom. This would cause the electrons to lose energy and to spiral into the nucleus.

An important step toward solving these problems was taken by Niels Bohr (1885-1962) in 1913. According to Bohr, the electrons in atoms cannot exist in arbitrary orbits. Instead they are found only in certain "states". The states in which they can exist are those in which the angular momentum of their orbits is an integer multiple of $h/2\pi$, where "h" is a quantity known as Planck's constant. This constant had been introduced by Max Planck (1858-1947) in his theory describing blackbody radiation.

According to the Bohr model of the atom, there is a so-called ground state for any atom. This ground state has the lowest energy allowed to the atom, and it is the same for all atoms containing the same number of electrons. An atom normally exists in this ground state, which determined the observed properties of a given element. Furthermore, according to Bohr, no radiation is emitted by an atom in its ground state. This is because energy must be conserved in the radiation process, and no available state of lower energy exists for the atom to balance any energy lost through radiation.

An atom can be removed from its ground state only when enough energy is given to it, by radiation or collisions, to raise an electron to an "excited" state. When the atom is excited, it will usually emit electromagnetic radiation rapidly and return to the ground state. The radiation is emitted in the form of individual packets or quanta, of light, called photons. Each photon has an energy equal to the difference between the energy of the excited states and the ground state of the atom. According to a formula developed by Planck and Einstein, this energy corresponds to a specific wavelength of the emitted light. Using this assumption about the allowed angular momenta for electrons, Bohr was able to calculate the precise wavelengths in the spectrum of the simplest atom, hydrogen.

In 1869, Dimitri I. Mendeléev (1834-1907) stated the rule that chemical elements arranged

according to the value of their atomic weights exhibit a clear periodicity of properties. Eventually, Bohr was able to extend his atomic theory to describe, qualitatively, the chemical properties of all the elements. Each electron in an atom is assigned a set of four so-called quantum numbers. These numbers correspond to the properties of energy, total orbital angular momentum, projection of orbital angular momentum, and projection of spin angular momentum. It is also assumed - as had first been suggested by Wolfgang Pauli (1900-1958) in 1924 - that no two electrons in an atom can have the same values for all four quantum numbers. This came to be known as Pauli's exclusion principle. This principle influences the way in which the chemical properties of an element depend on its atomic number, that is the number of electrons in each atom of the element. A maximum number of electrons can occur for each energy level, and no more than that. For example, the lowest energy level of an atom - the one in which the electrons have zero orbital angular momentum - can contain up to two electrons. The one electron in a hydrogen atom exists at this energy level, as do the two electrons in a helium atom. For the next heavier atom, lithium, one of its three electrons must exist in a higher energy state, and as a result this electron can more easily be lost to another atom. Those electrons with approximately the same energy are said to form a "shell".

Although Bohr's model gives a qualitatively accurate description of atoms, it does not give quantitatively accurate results for atoms more complex than hydrogen. In order to describe such atoms, it is necessary to use quantum mechanics. This theory of atomic and subatomic phenomena was created by Erwin Schrödinger (1887-1961), Werner Heisenberg (1901-1976), Paul Dirac (1902-1984), and Pascual Jordan (1902-1980) in the 1920s. In quantum mechanics, the electron orbits are replaced by probability distributions that only indicate in which regions of space each electron is most likely to be found. An equation discovered by Schrödinger allows this distribution to be calculated for each atom. From the distribution, properties of the atom such as energy and angular momentum can be determined.

In the second stage, particle physics accommodated, through an analysis of isotopes of elements, that all atomic nuclei could be thought of as composed of two types of particles: the proton, which carries both mass and electric charge, and the neutron, which has about the same mass as a proton but is electrically neutral. This model was confirmed through the discovery (1932) of free neutrons by James Chadwick (1891-1974).

3.5 Neutron

Physicists by the late 1920s were convinced that they sufficiently understood the electronic structure of atoms. Attention therefore turned to the nucleus. It was already known that nuclei sometimes change into one another through radioactive decay. Rutherford had also shown, in 1919, that this could be accomplished artificially by bombarding nitrogen nuclei with high-energy alpha particles. In the process the nitrogen nucleus is converted into an oxygen nucleus, and a hydrogen nucleus, or proton, is ejected. It had further been discovered by Joseph J. Thomson, Francis W. Aston (1877-1945), and others that for a given element the nucleus sometimes occurs in several different forms that differ in mass. These chemically similar but physically distinct atoms were called isotopes. All of this provided evidence that atomic nuclei also had some kind of internal structure that could be explored through experiments and

calculations.

Differences in the integer values of the electric charge and of the mass of many nuclei soon indicated that protons were not the only kind of particle to be found there. That is, the electric charge of a nucleus is always exactly an integer multiple of the charge of a proton, so knowledge of this electric charge always indicates how many protons a nucleus contains. The mass of a nucleus is also approximately - but not exactly - an integer multiple of the mass of a proton. For many atoms, however, these two integer values are not the same. For example, a helium nucleus has twice the charge but four times the mass of a proton. Clearly, nuclei contain something other than protons.

This problem was solved in 1932 with the discovery by James Chadwick of the neutron. This particle has no electric charge and is slightly more massive than a proton. Thus most nuclei are composed of both protons and neutrons, which collectively are known as nucleons. A helium nucleus contains two protons and two neutrons, which correctly give the total charge and mass of the nucleus. The isotopes of any given element contain equal numbers of protons but different numbers of neutrons. For example, an isotope of hydrogen, called deuterium, contains one proton and one neutron, and a heavier isotope, called tritium, contains one proton and two neutrons.

The problem then arose as to how atomic particles could be held together in such a small region as the nucleus. The force holding them had to be different from others then known to physicists. It was stronger than the electric forces that can break electrons away from nuclei. On the other hand, the nuclear forces between different nuclei that are far apart are very weak, much weaker than electric forces at such distances.

3.6   Fundamental Particles

The third stage of particle physics came with the recognition that protons, neutrons, and electrons - the constituents of ordinary matter - were but three of a vast number of similar particles, which differed only in a few properties, such as their mass, and in their stability against spontaneous decay. Experiments with particle accelerators indicated that these many subatomic particles could be readily produced from protons and neutrons, provided that enough energy was available to produce the additional mass of the new particles predicted by the rules of Einstein's relativity theory. These discoveries in the 1940s and 1950s indicated that the proton and neutron were not really fundamental particles and that they would have to be understood as part of a much larger family of similar objects.

By 1932 nuclei were known to be composed of protons and neutrons. It was then necessary to explain how nuclei were held together, and in 1935, the Japanese physicist Hideki Yukawa (1907-1981) predicted a smaller fundamental particle that was the carrier of a theorized strong interaction, one of the four fundamental interactions, or forces. This particle, called a π-meson, was discovered in 1947. Since then a host of particles smaller than protons and neutrons have been discovered in the nucleus, all falling within two classes: Fermions, which obey the Pauli exclusion principle, and bosons, which carry the fundamental force. Modern nuclear physics centers on fundamental interactions between fermions and bosons. Protons and neutrons are

composed of particles representing all four forces.

In the fourth stage, modern particle physics provided a successful explanation for the large number of particles. There are six different leptons: electron (e), muon (μ), tauon (τ), electron-neutrino (ν_e), muon-neutrino (ν_μ), and tau-neutrino (ν_τ). There are also six quarks denoted up (u), down (d), charm (c), strange (s), top (t), and bottom (b). For each of these particles there exists an anti-particle. Many of the models for particle interactions pair the leptons and quarks into families: $(e - \nu_e), (\mu - \nu_\mu), (\tau - \nu_\tau)$, and (u-d), (c-s), (t-b). Experiments suggest that it is unlikely that there are more than these families. The interactions between these fundamental particles are mediated by gauge bosons (photon, intermediate bosons $W^\pm$ and Z^0, gluons).

4 WEAK, ELECTROMAGNETIC, AND STRONG INTERACTIONS: STRUCTURE OF THE MICROCOSMOS

4.1 Fundamental Interactions

At sufficiently low energies, there are four types of fundamental interactions whose existence is well established. Most studied are two of them: The gravitational and the electromagnetic interactions. The foundations of the classical (non-quantum) theory of the two interaction types were laid long time ago by Newton and Maxwell.

In particle physics, the Standard Model encompasses all the particles known today and three of the fundamental interactions. The basic building blocks are two sets of matter particles, the quarks and the leptons (Table 1). These particles interact with each other through the exchange of

TABLE 1.

gauge bosons (see Section 4.3, Table 2.). The three fundamental interactions of the Standard Model are the electromagnetic, the strong, and the weak interactions, respectively. Gravity remains outside the Standard Model, but this does not invalidate the model as gravitational effects on particles are far smaller than the effects of the other interactions. The Standard Model has two components. One is the theory of strong interaction, called quantum chromodynamics. The other component is the theory that gives a unified description of electromagnetic and weak interactions, called the electroweak theory. The physical concepts used in the Standard Model are generalizations of concepts familiar in quantum electrodynamics (Kolb and Turner, 1990; Kaku, 1993).

4.1.1 Gravitational interaction

Gravitational interaction that governs the motion of celestial bodies is characterized by Newton's constant $G = 6.7 \times 10^{-8} \ g^{-1} \ cm^3 \ s^{-2}$. An excellent approximation that describes the

gravitational interaction of two point masses m, a distance r apart, is Newton's formula,

$$F = \frac{Gm^2}{r^2}. \tag{1}$$

All fundamental particles are affected by gravity. The relativistic generalization of Newton's theory of gravity is Einstein's theory of general relativity.

4.1.2   Electromagnetic interaction

Electromagnetic interaction determines the motion of charged bodies and acts only on charged particles. In the general case, their law of motion is described by Maxwell's equations. In the quasistatic approximation, an analogue to Newton's law, the Coulomb approximation,

$$F = \frac{e^2}{r^2}, \tag{2}$$

proves to work well. Here, e denotes the charge of each point mass. The quantum field theory of electromagnetism, quantum electrodynamics, is the best theory available for describing effects of the electromagnetic force. One of this theory's important features is its gauge symmetry, which means that when independent changes to local field values are made at different points in space, the equations of quantum electrodynamics are not changed. This symmetry is ensured only if the quantum description of a charged particle contains an electromagnetic field with its gauge boson, i.e., the gauge symmetry demands the existence of the electromagnetic force and the photon. The symmetry is also linked to the ability to renormalize quantum electrodynamics so that it yields sensible, finite results.

The magnitudes of Gm^2 and e^2 depend on the choice of the system of units. To facilitate comparison in the framework of quantum field theory, one combines these quantities with universal physical constants, the Planck constant $\hbar$ and the velocity of light c, to obtain dimensionless constants. Thus, the nondimensional gravitational constant (Table 3),

$$\alpha_g = \frac{Gm^2}{\hbar c}, \tag{3}$$

and the nondimensional electromagnetic fine structure constant (Table 3),

$$\alpha_e = \frac{e^2}{\hbar c}, \tag{4}$$

are obtained, $e \approx 10^{-19} C$ being the electron (proton) charge. There is a difference in the definition of the two constants, α_e being in a way more universal than α_g. The definition of the number α_e contains fundamental constants only, whereas the constant α_g involves a mass m which is, generally speaking, arbitrary. To eliminate this arbitrariness, it is common to fix the value of m by setting it equal to the proton mass m_p. This choice is quite natural, for the proton is one of the two stable particles constituting the structure of the universe; the other one is the electron, with mass m_e. The choice between m_p and m_e is a matter of convention ($m_p \approx 1837 m_e$).

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4.1.3   Weak interaction

The weak interaction governs the decay of particles into lighter ones and acts upon all quarks and leptons, including those with no electric charge. Historically, the first decay discovered was the decay of a neutron within an atomic nucleus (the β-decay), according to the reaction $n \to p + e^- + \bar{\nu}$ $(n, p, e^-, \text{and } \bar{\nu}$ denoting a neutron, a proton, an electron, and an antineutrino, respectively). Subsequently, the discovery of new particles was intensified by progress in the development of accelerators. It turned out that all newly discovered particles have a common property: Heavy particles decay into lighter ones. Numerous investigations led to the conclusion that many decays are controlled by a unique interaction, referred to as the weak interaction, which is characterized by the Fermi coupling constant $g_F = 10^{-49} \ erg \ cm^3$. The corresponding dimensionless coupling constant for the weak interaction is (Table 3)

$$\alpha_w = g_F \frac{m^2 c}{\hbar^3}. \tag{5}$$

The processes of collisions of neutrinos with matter are determined by the weak interaction as well.

There are many attempts to develop unified descriptions of all four interactions. In quantum theory every particle is associated with a particular field. How such a field transform under the Lorentz transformation depends on the spin of the particle described by the respective field. A zero-spin particle can be described by a scalar field (Higgs field), a spin-half particle by a spinor field, a spin-one particle by a vector field. The Lagrangian describing the field will carry information about the mass of the particle and its interactions. It is possible to construct a model that describes electromagnetic and weak interactions using a Lagrangian which possesses invariance under two transformation groups, U(1) and U(2).

The Higgs fields have a Lagrangian with a potential $V(\phi)$ which has non-trivial minima. If such a system comes into contact with matter fields which are in thermal equilibrium at some temperature T, then the effective potential energy will acquire a temperature dependence. That is, $V(\phi)$ will become $V(\phi, T)$. Such a temperature dependence can lead to several non-trivial effects - like phase transitions - in the early universe (Kolb and Turner, 1988). Even though the transformation group underlying the theory can be determined from some general principles, the detailed transformation properties of the fields representing specific particles cannot be derived from any fundamental considerations. These details are fixed using the known laboratory properties of these particles. For example, consider the fields describing the leptons. Given a spinor field ψ one can construct its 'right-handed' and 'left-handed' components by the decomposition

$$\psi_L = \frac{1}{2}(1 - \gamma_5)\psi; \quad \psi_R = \frac{1}{2}(1 + \gamma_5)\psi; \tag{6}$$

where γ_5 is the 4 x 4 matrix

$$\gamma_5 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}. \tag{7}$$

In the standard electroweak theory, the right-handed components behave as singlets (that is, they do not change) while the left-handed components transform as a doublet (that is, under an SU(2) transformation these fields are changed into linear components of themselves). It is a consequence of this feature that in the simplest electroweak theory there is no necessity for the right-handed neutrino, ν_R, and that the left-handed neutrino ν_L is massless. Since the transformation properties of the fields are put in by hand into the theory, it is possible to generalize these models in many ways. In particular, it is possible - though not necessary - to have massive neutrinos in the theory. This arbitrariness is of great importance for the existence of dark matter in the universe and for the solar neutrino problem.

4.1.4 Strong interaction

The strong interaction was identified with the nuclear interaction which acts only on quarks and is ultimately responsible for binding protons and neutrons within the nucleus. The attempts to develop a consistent theory of nuclear interaction took a long time. A breakthrough was achieved with the progress of the dynamical theory of quark systems that led to the advent of quantum chromodynamics. In that scheme, the nuclear interaction was identified with the interaction in many-quark systems. It is instructive to trace briefly the evolution of the quark interpretation of nuclear interaction. To do so, we briefly outline the quark model proposed by Murray Gell-Mann (b.1929) and George Zweig (b.1937) in 1964. According to this model, each proton and neutron consists of three point-like particles which are referred to as quarks and possess a charge that is a fraction of the electron charge e, $\pm\frac{1}{3}e$ or $\pm\frac{2}{3}e$. This theoretical conclusion was seemingly in contradiction to the experimental evidence that all the observable particles have an integer electric charge. Nevertheless, numerous experimental confirmations of the quark hypothesis (such as systematics of the elementary particles, the magnitude of the magnetic moments, the ratios of the interaction cross-sections, etc.) suggested that it deserves serious consideration. But then a profound question arose: How can the existence of quarks be reconciled with their nonobservability in experiments? At present, this problem is referred to as that of quark-confinement. A postulate is invoked which has rather a character of a magic: Quarks do exist, but in bound states. Even though no final solution of the confinement problem is available, one bases some expectations on the construction of a mathematical model that claims to provide a theory of the interaction between the quarks. It is this interaction that is identified with the strong interaction governing nuclear interaction. In 1954, Chen N. Yang (b.1922) and Robert L. Mills (b.1927) proposed a theory which is basically different from electrodynamics, but accounts for the interaction caused by the transfer of zero-mass particles. The only particle known at that time was the photon. The photon is the gauge particle in electrodynamics. That is why the Yang-Mills theory was considered just mathematical exercise. The picture changed, when a need emerged for a theory describing the dynamics of quarks. It seemed natural to consider the massless particles introduced by Yang and Mills to be responsible for the quark interaction. These particles were named gluons; by analogy with quantum electrodynamics, the quantum field theory of electromagnetism, one of the variants of the Yang-Mills theory is referred to as quantum chromodynamics. While gluons are analogues of photons, quarks are analogues of electrons. They carry not only color charges but also

ordinary electric charge. E.g., a proton consists of three quarks ($p = uud$), a neutron consists of three quarks ($n = udd$), held together by continuing exchange of gluons. In the early 1970's the Yang-Mills equations were subjected to more scrutiny. As a result, the constant α_s was found to exhibit quite remarkable behavior, as distinct from quantum electrodynamics. This constant determines the quark-quark interaction which is currently believed to be the true strong interaction. It should be remembered that from the viewpoint of contemporary field theory the interaction is mediated by gauge bosons, i.e., quanta of the corresponding field. Energy-momentum and hence - according to the special theory of relativity - mass is transferred along with a quantum. Elaborate calculations have demonstrated that the strong interaction coupling constant α_s essentially depends on the energy-momentum and the mass m transferred. In a way, one had encountered a mass dependence of the constants α before (e.g., α_g and α_w), but quantum chromodynamics introduces a basic difference. In this theory, the dependence $\alpha_s(m)$ is deduced from quantum field theory, and not postulated, as was done earlier for the constants, α_g and α_w, on the basis of dimensional considerations. In addition, the variation of the constant α_s with the mass m has a specific feature: α_s decreases with increasing m. It should be remarked here that the terminology repeatedly used above might appear contradictory. On the one hand, one speaks of the constants α; on the other hand, one keeps stressing their dependence on m. In fact, the constants α are only constant at a fixed m; they vary with changing m. That is why they are referred to as "running" constants. The final expression for the dependence of α_s on m reads, in the asymptotic approximation when $m >> m_p$ (Table 3):

$$\alpha_s \sim \frac{a}{ln(\frac{m}{m_p})}. \tag{8}$$

The quantity a depends on N_q, the number of the sorts of quarks. In a standard theory ($N_q = 6$), $a \sim 1$. It follows from this formula that $\alpha_s \rightarrow 0$ as $m \rightarrow \infty$. This is the phenomenon of asymptotic freedom. A similar dependence also follows from a more exact expression. Unfortunately, the latter has been also obtained by methods whose validity breaks down for $m < m_p$. A "true" expression for α_s at small m is missing, owing to the fact that α_s is large, thus rendering standard computation techniques inapplicable. One can only state that for a small characteristic mass m, corresponding to the proton (or neutron) size, $r_N \approx 10^{-13}$ cm, the coupling constant is large. Furthermore, a rapid increase of the constant α_s, with r approaching r_N inhibits progress in solving another problem, namely, that of nuclear forces. Today, quantum chromodynamics is considered as a theory that describes the interactions among quarks and gluons, out of which atomic nuclei are made.

4.2   Classification of Fundamental Particles

Fundamental particles are classified with respect to various parameters. A particle classification appears to be provided by the value of the spin, s. The behavior of particles depends on whether their spin is characterized by an integer $(0, 1, 2, \dots)$ or a half-integer $(1/2, 3/2, 5/2, \dots)$. Particles with a half-integer spin are referred to as fermions, while those with an integer spin as bosons. In the framework of quantum mechanics, the difference in the behavior of fermions and bosons is expressed by the kind of symmetry of the wave functions describing these particles. A

system consisting of fermions obeys Pauli's exclusion principle, as distinct from a boson system on which no such exclusion principle is imposed. Pauli's principle reads as follows: No two fermions may be in exactly the same quantum state.

An excellent illustration of Pauli's principle is the atomic level structure underlying the periodic system of the chemical elements. It is known that the first period of this system is composed of two elements, hydrogen and helium. For the first period, the principal quantum number equals unity. The atomic states associated with the first period are therefore determined only by the value of the spin projection of orbital electrons. There are two such values. Thus, only two elements can occur in the first period. For the second period, the principal quantum number equals two, giving rise to eight possible different states and thus to eight elements, etc. The Pauli principle is one of the foundations of the very structure of the periodic system. If this principle did not work, all the atomic electrons would populate the ground energy level (i.e., the hydrogen level), and, consequently, the periodicity of the system as well as the valency of chemical bonding would vanish. It is the Pauli principle that prevents atomic electrons from occupying the energetically most favorable ground state.

Another basis for the classification of the fundamental particles is their interaction. All particles participating in the strong interaction are referred to as hadrons (from the Greek word "hadros", meaning "strong"). All fermions which do not participate in the strong interaction are called leptons. A special place in this classification is reserved for the bosons, particles which mediate the interactions. The hadrons, in turn, are subdivided into the baryons and the mesons. The baryons are fermions; the lightest baryon is the proton. The hadrons with integer spin are referred to as mesons; the lightest meson is the pion ($m_\pi \approx 140 \ MeV$).

4.3 How Fundamental Particles Interact

Particles interact by exchange of gauge bosons; the exchange in the process of interaction involves not only energy, momentum, and mass, but also the internal quantum numbers: spin, isospin, charge, and color. The properties of the exchange particles in the context of quantum field theory determine the interaction to a great extent. All exchange particles are bosons. The properties of the exchange particles are summarized in Table 2.

TABLE 2.

4.3.1 Graviton

The graviton is a massless particle with zero charge and a spin $s = \pm \, 2$ and has not been detected owing to its extremely weak interaction. Although most physicists have no doubts about the existence of gravitons, some caution is advisable, since the quantum theory of gravitation itself is far from being complete. Because of the weakness of the gravitational field, there is no hope for rapid progress in detecting and investigating gravitons. Because the graviton is a massless particle, the gravitational interaction is long range.

4.3.2 Photon

Photons have spins of $s = \pm 1$, a rest mass of zero, and are their own antiparticles. The electromagnetic interaction has a long range because the photon is massless.

4.3.3 Intermediate bosons

The weak interaction is mediated by three intermediate gauge bosons $W^\pm$ and Z^0 which have masses of ~ 80 GeV and ~ 91 GeV, respectively. Since the range of an interaction is inversely related to the mass of the gauge boson, the weak interaction has an extremely short range.

4.3.4 Gluons

The gluons, like the quarks, are not observable in the free state. However, in the late 1970's, considerable progress in the indirect verification of gluons was achieved by investigating the annihilation of high-energy positrons and electrons with hadron generation. It turned out that three hadronic jets occur in such processes; two jets are attributed to quarks and the third one, to gluons. The experimental data on the three-jet processes accompanying positron-electron annihilation are in good agreement with the predictions of quantum chromodynamics, which indirectly confirms the existence of gluons, one of the basic elements of that theory. The strong interaction is mediated by a set of gauge bosons, containing at least eigth gluons.

The data presented in Table 3 list the properties of the four interactions. A new entry here is the value of the interaction radius. For the gravitational, the weak, and the electromagnetic interaction, the magnitude of the radius r is determined from the uncertainty relation, $\hbar/m_B c$, m_B denoting the mass of an exchange particle. In the case of the strong interaction, the interaction radius, r_N, may be regarded either as an empirical constant or as the distance at which the value of the coupling constant α_s becomes unity.

TABLE 3

5   GRAVITATIONAL INTERACTION: STRUCTURE OF THE MACROCOSMOS

5.1   Structural Elements of the Universe

The structure of the macrocosmos is manifested on many different scales, ranging from the universe on the largest scale, down to galaxies, stars, and planets. Only objects of the microcosmos, such as quarks and leptons, may be devoid of further substructure (However, a recent experiment is suggesting that quarks and gluons may be composed of more fundamental particles (Wilczek, 1996)). Most scales are determined to an order of magnitude by a few physical constants. In particular, the mass scale and length scale (in units of the proton mass m_p and the Bohr radius a_0) of structures down to the planets can be expressed in terms of the electromagnetic fine structure constant α_e, eq.(4), the gravitational fine structure constant α_g eq.(3), and the electron-to-proton mass ratio ($m_p \approx 1837 m_e$).

The following considerations are based on order of magnitude arguments, factors of order unity (like π) being neglected. These results have been published in the astrophysical literature at several occasions and are collected here for easy reference (a detailed discussion is contained in Carr and Rees, 1979; Barrow and Tipler, 1988).

5.1.1 The Planck scales

The only quantities of dimensions mass and length which can be constructed from $G, \hbar$ and c are the Planck scales:

$$M_{Pl} \sim (\frac{G}{\hbar c})^{-1/2} \sim 10^{-5} \ g, \quad R_{Pl} \sim (\frac{G}{\hbar c^3})^{1/2} \sim 10^{-33} \ cm. \tag{9}$$

Using the gravitational fine structure constant, eq.(3), these scales can be expressed as

$$M_{Pl} \sim \alpha_G^{-1/2} m_p, \quad R_{Pl} \sim \alpha_G^{1/2} r_p. \tag{10}$$

Thus M_{Pl} is much larger than m_p but R_{Pl} is much smaller than r_p (r_p being the size of a proton that can be taken to be the Compton wavelength associated with its rest mass, $r_p \sim \hbar/m_p c \sim 10^{-13} \ cm$; accordingly, the corresponding timescale is $t_p \sim r_p/c \sim 10^{-23} \ s$). The Planck length is the scale on which quantum gravitational fluctuations in the metric become of the order of unity, so the concept of space breaks down at such small scales. M_{Pl} can be interpreted as the mass of a black hole of radius R_{Pl}. Space may be thought of as being filled with virtual black holes of this size. Such "instantons" may play an important role in quantum gravity theory.

5.1.2 The Universe

In the simplest Friedmann cosmological model, the age of the universe t_0, is of the order of H_0^{-1} where H_0 is the Hubble parameter (this relation fails only if the universe is closed and near its maximum expansion). Since $H_0 \sim 50 \ km \ s^{-1} \ Mpc^{-1}$, this implies $t_0 \sim 10^{10}$ yr, a conclusion which is supported by several independent arguments. The associated horizon size (the distance travelled by light since the birth of the universe) satisfies the approximate relationship

$$ct_0 \sim \alpha_g^{-1}(\frac{\hbar}{m_e c}) \sim (\frac{\alpha_e}{\alpha_g})a_0, \tag{11}$$

where a_0 denotes the radius of the lowest energy electron orbit of a hydrogen atom, $a_0 \sim \hbar^2/m_e e^2 \sim 10^{-8} \ cm \sim 1 \ Bohr$. The ratio of the size of the observable universe to the size of an atom is comparable with the ratio of the electrical (or nuclear) and gravitational forces between elementary particles. There is no explanation for this well known coincidence within conventional physics, but Dirac (1937, 1938) has conjectured that α_g is always given by

$$\alpha_g \sim \frac{\hbar}{m_e c^2 t} \sim (\frac{t}{t_e})^{-1}. \tag{12}$$

Assuming that $\hbar, c,$ and m_e are constant in time, this requires that G decreases as t^{-1}, so Dirac invokes eq.(12) as the basis for a new cosmology (Barrow, 1996). Such a variation of G is inconsistent with current observations. The total mass associated with the observable universe (the mass within the horizon volume) is $\sim \rho_0 \, c^3 \, t_0^3$, where ρ_0 is the present matter density, given by the Friedmann equation,

$$\rho_0 = \frac{3H_0^2}{8\pi G} + \frac{Kc^2}{16\pi G}. \tag{13}$$

Here K is the scalar curvature of the universe. Providing the K term is smaller than the others, one deduces that the mass of the universe is

$$M_u \sim c^3 t_0^3 G^{-1} H_0^2 \sim \frac{c^3 t_0}{G} \sim \alpha_g^{-2}(\frac{m_p}{m_e})m_p. \tag{14}$$

The fact that the number of protons in the universe is of the order of α_g^{-2}, is thus explained providing one can justify neglecting the K term in eq.(13). It has been argued that K must always be zero by appealing to Mach's principle but, apart from this, there may be reasons for expecting that the K term is small. If K is negative, galaxies could not have condensed out from the general expansion unless $(-K)$ were less than $G\rho/c^2$ at their formation epoch. Otherwise, their gravitational binding energy would not have been large enough to halt their expansion. The term $(-K)$ may exceed $G\rho/c^2$ at the present epoch, but not by a large factor. If K is positive, it must be $< G\rho_0/c^2$, otherwise the whole universe would have recollapsed before $t \simeq t_{MS}$, where t_{MS} is the lifetime of a typical main-sequence star, say, the Sun. Relationships (11) and (14) also mean that the universe has an optical depth of the order of unity to electron scattering.

5.1.3   Galaxies

It is not certain how galaxies form, so any estimate of their scale is very model dependent (Rees and Ostriker, 1977; Silk, 1977; Sciama, 1953). One can assume that galaxies originate from overdense regions in the gaseous primordial material, and that they have a mass M and radius R_B when they become bound. After binding, motions in the protogalaxy randomize and equilibrate in the gravitational field of the galaxy at a radius $\sim R_B/2$. Thereafter, they will deflate on a cooling timescale, with a virial temperature

$$T \sim \frac{GMm_p}{kR}. \tag{15}$$

Providing kT exceeds one Rydberg the dominant cooling mechanism is bremsstrahlung and the associated cooling timescale is

$$t_{cool} \simeq \frac{m_e^2 c^3}{\alpha_e e^4 n}(\frac{kT}{m_e c^2})^{1/2}. \tag{16}$$

The free-fall timescale is

$$t_{ff} \sim (\frac{GM}{R^3})^{-1/2}, \tag{17}$$

and this exceeds t_{cool} when R falls below a mass-independent value

$$R_g \sim \alpha_e^4 \alpha_g^{-1} (\frac{m_p}{m_e})^{1/2} a_0, \tag{18}$$

which, from a more precise calculation, is 75 kpc. Until a massive cloud gets within this radius it will contract quasi-statically and cannot fragment into stars. This argument applies only if the mass is so high that $kT_{virial} > \alpha_e^2 m_e c^2$ at the 'magic radius' R_g; that is,

$$M \geq M_g = \alpha_g^{-2} \alpha_e^5 (\frac{m_p}{m_e})^{1/2} \simeq 10^{12} M_\odot. \tag{19}$$

Gas clouds of mass $< M_g$ cool more efficiently owing to recombination, and can never be pressure supported. Thus, M_g is a characteristic maximum galactic mass. Primordial clouds of mass $< M_g$ are inhibited from fragmentation and may remain as hot pressure-supported clouds. This type of argument can be elaborated and made more realistic (White and Rees, 1978; Rees and Ostriker, 1977; Silk, 1977; Sciama, 1953); but one still obtains a mass $\sim M_g$ above which any fluctuations are likely to remain amorphous and gaseous, and which may thus relate to the mass-scale of galaxies. The quantities M_g and R_g may thus characterise the mass and radius of a galaxy. These estimates is the least certain. The properties of galaxies may be a consequence of irregularities imprinted in the universe by processes at early epochs.

5.1.4   Stars

The virial theorem implies that the gravitational binding energy of a star must be of the order of its internal energy. Its internal energy comprises the kinetic energy per particle (radiation pressure being assumed negligible for the moment) and the degeneracy energy per particle. The degeneracy energy will be associated primarily with the Fermi-momentum of the free electrons, $p \sim \hbar/d$, where d is their average separation. Provided the electrons are non-relativistic, the degeneracy energy is $p^2/2m_e$, so the virial theorem implies (Dyson, 1972; Weisskopf, 1975; Haubold and Mathai, 1994)

$$kT + \frac{\hbar^2}{2m_e d^2} \sim \frac{GMm_p}{R} \sim (\frac{N}{N_0})^{2/3} \frac{\hbar c}{d}. \tag{20}$$

Here N is the number of protons in the star, $N_0 \equiv \alpha_g^{-3/2}$, and $R \sim N^{1/3} d$ is its radius. As a cloud collapses under gravity, eq. (20) implies that, for large d, T increases as d^{-1}. For small d, however, T will reach a maximum

$$kT_{max} \sim (\frac{N}{N_0})^{4/3} m_e c^2, \tag{21}$$

and then decrease, reaching zero when d is

$$d_{min} \sim (\frac{N}{N_0})^{-2/3} r_e, \tag{22}$$

where r_e is the size of an electron, $r_e \sim \hbar/m_e c \sim 10^{-10}$ cm; accordingly the electron timescale is defined as $t_e = r_e/c \sim 10^{-20}$ s. A collapsing cloud becomes a star only if T_{max} is high enough for nuclear reactions to occur, that is $kT_{max} > qm_e c^2$ where q depends on the strong and electromagnetic interaction constants and is $\sim 10^{-2}$. From eq. (21), one therefore needs $N > 0.1N_0$. Once a star has ignited, further collapse will be postponed until it has burnt all its nuclear fuel. An upper limit to the mass of a star derives from the requirement that it should not be radiation-pressure dominated. Such a star would be unstable to pulsations which would probably result in its disruption. Using the virial theorem (that is, eq.(20) with the degeneracy term assumed negligible) to relate a star's temperature T to its mass $M \sim Nm_p$ and radius R, the ratio of radiation pressure to matter pressure can be shown to be

$$\frac{P_{rad}}{P_{mat}} \sim \frac{aT^4 R^3}{NkT} \sim (\frac{N}{N_0})^2, \tag{23}$$

so the upper limit to the mass of a star is also $\sim N_0 m_p$. A more careful calculation shows that there is an extra numerical factor of the order of 10, so one expects all main-sequence stars to lie in the range $0.1 < N/N_0 < 10$ observed. Only assemblages of $10^{56} - 10^{58}$ particles can turn into stable main sequence stars with hydrogen-burning cores. Less massive bodies held together by their own gravity can be supported by electron 'exclusion principle' forces at lower temperatures (they would not get hot enough to undergo nuclear fusion unless squeezed by an external pressure); heavier bodies are fragile and unstable owing to radiation pressure effects. The central temperature, T, adjusts itself so that the nuclear energy generation rate balances the luminosity, the radiant energy content divided by the photon leakage time,

$$L \simeq acT^4 R^4/\kappa M, \tag{24}$$

where κ is the opacity. The appropriate κ decreases as M increases (electron scattering being the dominant opacity for upper main-sequence stars) but the energy generation increases so steeply with T that M/R depends only weakly on M.

5.1.5 White dwarfs and neutron stars

When a star has burnt all its nuclear fuel, it will continue to collapse according to eq.(20) and, providing it is not too large, it will end up as a cold electron-degeneracy supported 'white dwarf' with the radius $R \propto M^{-1/3}$ indicated by eq.(22). However, when M gets so large that $kT_{max} \sim m_e c^2$, the electrons will end up relativistic, with the degeneracy energy being pc rather than $p^2/2m_e$. Thus the degeneracy term in eq.(20) acts as d^{-1} instead of d^{-2}, and consequently there is no $T = 0$ equilibrium state. From eq.(21) this happens if M exceeds the mass

$$M_c \sim \alpha_g^{3/2} m_p \sim 1M_\odot, \tag{25}$$

which characterises stars in general. A more precise expression for this critical value of M (Chandrasekhar mass) is $5.6\mu^2 M_\odot$, where μ is the number of free electrons per nucleon (Chandrasekhar, 1935). For a star which has burned all the way up to iron, $\mu \approx 1/2$ and the limiting Chandrasekhar mass, taking into account the onset of inverse β-decay when electrons get relativistic, is $\sim 1.25M_\odot$. Stars bigger than M_c will collapse beyond the white dwarf density

but may manage to shed some of their mass in a supernova explosion. The remnant core will comprise mainly neutrons, the electrons having been squeezed onto the protons through the reaction $p + e^- \rightarrow n + \nu$, and this core, if small enough, may be supported by neutron-degeneracy pressure. The limiting mass for a neutron star is more difficult to calculate than that for a white dwarf because of strong interaction effects and because, from eq.(21), with $m_e \rightarrow m_p$, the particles which dominate the neutron star's mass are relativistic. The maximum mass is still of the order of $1 M_\odot$, however, and a neutron star bigger than this must collapse to a black hole. The maximum mass lies close to the intercept of a black hole line, given by eq.(26), and the nuclear density line $\rho \sim m_p/r_p^3$. The intricacies of the line which bridges white dwarf and neutron star regimes reflect the effects of gradual neutronisation and strong interactions. Stars on this bridge would be unstable and so are not of immediate physical interest.

The above order-of magnitude arguments show why the effects of radiation pressure and relativistic degeneracy both become important for masses $> \alpha_g^{-3/2} m_p$. Note also that general relativity is unimportant for white dwarfs because the binding energy per unit mass is only $\sim (m_e/m_p)$ of c^2 at the Chandrasekhar limit.

5.1.6 Black holes

The radius of a spherically symmetrical black hole of mass M is

$$R = \frac{2GM}{c^2} \sim \alpha_g (\frac{M}{m_p}) r_p. \tag{26}$$

This is the radius of the event horizon, the region from within which nothing can escape, at least, classically. Black holes larger than $1 M_\odot$ may form from the collapse of stars or dense star clusters. Smaller holes require much greater compression for their formation than could arise in the present epoch, but they might have been produced in the first instants after the Big Bang when the required compression could have occurred naturally. Such 'primordial' black holes could have any mass down to the Planck mass. In fact, Hawking (1974) has shown that small black holes are not black at all; because of quantum effects they emit particles like a black body of temperature given by

$$k\theta \sim \frac{\hbar c^3}{GM} \sim \alpha_g^{-1} (\frac{M}{m_p})^{-1} m_p c^2. \tag{27}$$

This means that a hole of mass M will evaporate completely in a time

$$t_{evap} \sim \alpha_g^2 (\frac{M}{m_p})^3 t_p (N(\theta))^{-1}. \tag{28}$$

$N(\theta)$ is the number of species contributing to the thermal radiation: For $k\theta < m_e c^2$ these include only photons, neutrinos, and gravitons; but at higher temperatures other species may contribute. The evaporation terminates in a violent explosion. For a solar mass hole, this quantum radiance is negligible: θ is only 10^{-7} K and $t_{evap} \sim 10^{64}$ yr. But for small holes it is very important. A Planck mass hole has a temperature of 10^{32}K and only survives for a time $\sim R_{Pl}/c \sim 10^{-43}$ s. Those holes which are terminating their evaporation in the present epoch

are particularly interesting. As the age of the universe is $t_0 \sim \alpha_g^{-1} t_e$, the mass of such holes would be

$$M_h \sim \alpha_g^{-2/3} (\frac{t_0}{r_p})^{1/3} m_p \sim \alpha_g^{-1} m_p \sim 10^{15} \ g, \tag{29}$$

and , from eq.(26), their radius would be r_p. The corresponding temperature is ~ 10 MeV: Low enough to eliminate any uncertainty in $N(\theta)$ due to species of exotic heavy particles.

5.2 Evolution of the Universe

The origin of the universe is governed by laws of physics which are still unknown at the time of writing the Encyclopedia of Applied Physics (see Fig.6).

FIGURE 6.

At $t = 10^{-43} \ sec, T = 10^{32} \ K$: The strong, weak, and electromagnetic forces may appear as unified into one indistinguishable force. This period is often referred to as the Grand Unification epoch. During this epoch, there may have been a very rapid, accelerating expansion of the universe called "inflation". The inflation made the universe very large and flat, but also produced ripples in the space-time it was expanding.

At $t = 10^{-34} \ sec, T = 10^{27} \ K$: The strong force becomes distinct from the weak and electromagnetic forces. The universe is a plasma of quarks, electrons, and other particles. Inflation ends and the expanding universe coasts, gradually slowing its expansion under the pull of gravity.

At $t = 10^{-10} \ sec, T = 10^{15} \ K$: The electromagnetic and weak forces separate (see Fig.7). An excess of one part in a billion of matter over antimatter has developed. Quarks are able to merge to form protons and neutrons. Particles have acquired substance.

FIGURE 7.

At $t = 1 \ sec, T = 10^{10} \ K$: Neutrinos decouple and the electrons and positrons annihilate, leaving residual electrons but predominantly the cosmic background radiation as the main active constituent of the universe.

At $t = 3 \ min, T = 10^9 \ K$: Protons and neutrons are able to bind together to form nuclei since their binding energy is now greater than the cosmic background radiation energy. A rapid synthesis of light nuclei occurs - first deuterium (D), then heavier elements, primarily helium ($^3He, ^4He$) but up to lithium nuclei ^7Li (Tytler, Fan, and Burles, 1996; Gloeckler and Geiss, 1996). About 75 percent of the nuclei are hydrogen and 25 percent are helium; only a tiny amount are other elements. The heavier elements are later formed by nuclear burning stars.

At $t = 3 \times 10^5 \ yr, T = 3 \times 10^3 \ K$: Matter and the cosmic background radiation decouple as electrons bind with nuclei to produce neutral atoms. The universe becomes transparent to the cosmic background radiation, making it possible for the Cosmic Background Explorer satellite (COBE) to map this epoch of last scattering (see Fig.8).

A $t = 10^9$ $yr, T = 18$ K: Clusters of matter have formed from the primordial ripples to form quasars, primordial stars, and protogalaxies. In the interior of stars, the burning of the primordial hydrogen and helium nuclei synthesizes heavier nuclei such as carbon, nitrogen, oxygen, and iron. These are dispersed by stellar winds and supernova explosions, making new stars, planets, and life possible.

At $t = 15 \times 10^9$ $yr, T = 3$ K: The present epoch is reached (see Fig.9). Five billion years earlier, the solar system condensed from the remnants of earlier stars. Chemical processes have linked atoms together to form molecules and then solids and liquids. Man has emerged from the dust of stars to contemplate the universe around him.

5.3 Large-Scale Distribution of Matter

The nearest large galaxy to the Milky Way is the 'Andromeda galaxy' which is about 670 kpc away. Its mass is $\sim 3 \times 10^{11} M_\odot$ or perhaps as much as $1.5 \times 10^{12} M_\odot$ if it has a massive halo) and it has a size of ~ 50 kpc. Studies show that it is a spiral galaxy. The Andromeda galaxy and the Milky Way lie nearly in each other's planes, but their spins are opposite. It may be noted that galaxies are packed in the universe in a manner very different from the way the stars are distributed inside a galaxy: The distance from the Milky Way to the nearest large galaxy is only 20 galactic diameters while the distance from the Sun to the nearest star is thirty million times the diameter of such individual stars. There is some evidence to suggest that the Andromeda galaxy and the Milky Way are gravitationally bound to each other. They have a relative velocity - towards each other - of about 300 km s^{-1}. These two are only the two largest members of a group of more than 30 galaxies all of which together constitute what is known as the 'Local Group'. The entire Local Group is irregular in shape and can be contained within a spherical volume of ~ 2 Mpc in radius. This kind of clustering of galaxies into groups is typical in the distribution of the galaxies in the universe. A study within a size of about 20 Mpc from the Milky Way shows that only (10-20)% of the galaxies do not belong to any group; they are isolated galaxies, called 'field' galaxies. Groups may typically consist of up to 100 galaxies; a system with more than 100 galaxies is conventionally called a 'cluster'. The sizes of groups range from a few hundred kpc to 2 Mpc. Clusters have a size of typically a few Mpc. Just like galaxies, one may approximate clusters and groups as gravitationally bound systems of effectively point particles. The large gravitational potential energy is counterbalanced by the large kinetic energy of random motion in the systems. The line of sight velocity dispersion in groups is typically 200 km s^{-1} while that in clusters can be nearly 1000 km s^{-1}.

There are several similarities between clusters of galaxies and stars in an elliptical galaxy. For example, the radial distribution of galaxies in a cluster can be adequately fitted by the $R^{1/4}$ law with an effective radius $R_e \approx (1-2)h^{-1} Mpc$ ($0.5 \leq h \leq 1$ related to the Hubble constant). About 10% of all galaxies are members of large clusters. In addition to galaxies, clusters also contain very hot intracluster gas at temperatures $(10^7 - 10^8)$ K. The two large

clusters nearest to the Milky Way are the Virgo cluster and the Coma cluster. The Virgo cluster, located ~ 17 Mpc away, has a diameter of about 3 Mpc and contains more than 2500 galaxies. This is a prominent irregular cluster and does not exhibit a central condensation or a discernible shape. Virgo has an intracluster X-ray emitting gas with a temperature of $\sim 10^8$ K, which has at least ten times the visible mass of the cluster. The Coma cluster, on the other hand, is almost spherically symmetric with a marked central condensation. It has an overall size of ~ 3 Mpc while its central core is ~ 600 kpc in size. The core is populated with elliptical and spheroidal galaxies with a density nearly thirty times larger than the Local Group. These values are typical for large clusters. Coma is located at a distance of ~ 80 Mpc and contains more than 1000 galaxies. The distribution of galaxies around the Local Group has been studied extensively. It turns out that most of the galaxies nearby lie predominantly in a plane - called the super-galactic plane - which is approximately perpendicular to the plane of the Milky Way galaxy. The dense set of galaxies in this plane is called the Local Supercluster (radius ~ 37 Mpc) and the Virgo cluster is nearly at the centre of this highly flattened disc-like system. The term 'supercluster' is just used to denote structures bigger than clusters. Broadly speaking, the Local Supercluster consists of three components: About 20% of the brightest galaxies, forming the core, is the Virgo cluster itself; another 40% of galaxies lie in a flat disc with two extended, disjoint groups of galaxies; the remaining 40% is confined to a small number of groups scattered around. Nearly 80% of all matter in the Local Supercluster lies in a plane . The Local Supercluster is clearly expanding. Studies of distant galaxies show that there are many superclusters in our universe separated by large voids. The distribution of matter seems to be reasonably uniform when observed at scales bigger than about 100 h^{-1} Mpc. For comparison, note that the size of the observed universe is about 3000 h^{-1} Mpc. Thus, one may treat the matter distribution in the universe to be homogeneous while dealing with the phenomena at scales larger than 100 Mpc. The standard cosmological model is based on this assumption of "large scale" homogeneity (see Fig.10 and Table 4; Geller and Huchra, 1989).

FIGURE 10.

5.4   Morphology of Galaxies

Galaxies range widely in their sizes, shapes, and masses; nevertheless, one may talk of a typical galaxy as something made out of $\sim 10^{11}$ stars. Taking the mass of a star to be that of the Sun, the luminous mass in a galaxy is $\sim 10^{11} M_\odot \approx 2 \times 10^{44}$ g. This mass is distributed in a region with a size of ~ 20 kpc. Even though most galaxies have a mass of $\sim (10^{10} - 10^{12}) M_\odot$ and a size of $\sim (10 - 30)$ kpc, there are several exceptions at both ends of this spectrum. For example, 'warf galaxies' have masses in the range $\sim (10^5 - 10^7) M_\odot$ and radii of $\sim (1 - 3)$ kpc. There are also some 'giant galaxies' with masses as high as $10^{13} M_\odot$. Galaxies exhibit a wide variety in their shapes as well and are usually classified according to their morphology (Hubble's classification of galaxies, for example). One may divide them into 'ellipticals' and 'discs'. Ellipticals are smooth, featureless, distributions of stars, ranging in mass from $10^8 M_\odot$ to $10^{13} M_\odot$. The proportion of elliptical galaxies in a region depends sensitively on the environment. They contribute $\sim 10\%$ of all galaxies in low density regions of the universe but $\sim 40\%$ in dense

clusters of galaxies. The second major type of galaxy is the 'piral' (or 'disc') to which the Milky Way belongs. Spirals have a prominent disc, made of Population I stars and contain a significant amount of gas and dust. The name originates from the distinct spiralarms which exist in many of these galaxies. In low density regions of the universe, $\sim 80\%$ of the galaxies are spirals while only $\sim 10\%$ of galaxies in dense clusters are spirals. This is complementary to the behavior of ellipticals. The stars in a disc galaxy are supported against gravity by their systematic rotation velocity. The rotational speed of stars, $v(R)$, at radius R has the remarkable property that it remains constant for large R in almost all spirals; the constant value is typically 200-300 $km\ s^{-1}$. Most discs also contain a spheroidal component of Population II stars. The luminosity of the spheroidal component relative to the disc correlates well with several properties of these galaxies. This fact has been used for classifying the disc galaxies into finer divisions. The stars in a galaxy are not distributed in completely uniform manner. A typical galaxy contains several smaller stellar systems, each containing $\sim (10^2 - 10^6)$ stars. These systems, usually called star clusters, can be broadly divided into two types called 'open clusters' and 'globular clusters'. Open clusters consist of $\sim (10^2 - 10^3)$ Population I stars bound within a radius of $\sim (1 - 10)$pc. Most of the stars in these clusters are quite young. In contrast, globular clusters are Population II systems with $\sim (10^4 - 10^6)$ stars. The Milky Way contains ~ 200 globular clusters which are distributed in a spherically symmetric manner about the centre of the galaxy. Unlike open clusters, the stars in globular clusters are quite old. The number density of stars in the core of a globular cluster, $\sim 10^4 M_\odot\ pc^{-3}$, is much higher than that of a typical galaxy, $\sim (0.05 M_\odot\ pc^{-3}$. The core radius of the globular clusters is ~ 1.5 pc while the 'tidal radius', which is the radius at which the density drops nearly to zero, is ~ 50 pc. In addition to the stars, the Milky Way also contains gas and dust which contribute $\sim (5 - 10)\%$ of its mass. This interstellar medium may be roughly divided into a very dense, cold, molecular component (with about 10^4 particles per cm^{-3} and a temperature of ~ 100 K), made of interstellar clouds, a second component which is atomic but neutral, (with $n \approx 1\ cm^{-3}$ and $T \approx 10^3\ K$) and a third component which is ionized and very hot (with $n \approx 10^{-3}\ cm^{-3}$ and $T \approx 10^6\ K$). Though the interstellar medium is principally made of hydrogen, it also contains numerous other chemical species and an appreciable quantity of tiny solid particles ('dust'). The spiral arms are concentrations of stars and interstellar gas and are characterized by the presence of ionized hydrogen. This is also the region in which young stars are being formed. For a more detailed study of galaxies, one can divide ellipticals and spirals into subsets and also add two more classes of galaxies, called 'lenticulars' and 'irregulars'. The ellipticals are subdivided as (E1, . . ., En, . . .) where $n = 10(a - b)/a$ with a and b denoting the major and minor axis of the ellipticals. The 'lenticulars' (also called SO) are the galaxies 'in between' ellipticals and spirals. They have a prominent disc which contains no gas, dust, bright young stars or spiral arms. Though they are smooth and featureless like ellipticals, their surface brightness follows the exponential law of the spirals. They are rare in low density regions (less than 10%) but constitute nearly half of the galaxies in the high density regions. The spirals are subdivided into Sa, Sb, Sc, Sd with the relative luminosity of the spheroidal component decreasing along the sequence. The amount of gas increases and the spiral arm becomes more loosely spiraled along the sequence from Sa to Sd. The Milky Way is between the types Sb and Sc. There also exists another class of spirals called 'barred spirals' which exhibit a bar-like structure in the centre. They are classified as

SBa, SBb etc. Finally, irregulars are the galaxies which do not fall in the above mentioned morphological classification. These are low luminosity, gas rich systems with massive young stars and large HII regions (i.e. regions containing ionized hydrogen). More than one third of the galaxies in our neighborhood are irregulars. They are intrinsically more difficult to detect at larger distances because of their low luminosity. We have seen earlier that as the stars evolve, their luminosity and hence the color changes. Since galaxies are made of stars, galaxies will also exhibit color evolution. Besides, the gas content and elemental abundances of the galaxies will change as the stars are formed and end as planetary nebulae or supernovae.

5.5   Quasars

Most galaxies which are observed have a fairly low redshift ($z < 0 - 5$) and an extended appearance on a photographic plate. There exists another important class of objects, called 'quasars', which exhibit large redshifts (up to $z \approx 5$) and appear as point sources in the photographic plate (Shaver et al., 1996). Estimating the distance from the redshift and using the observed luminosity, it is found that quasars must have a luminosity of about $L_q \approx (10^{46} - 10^{47})\ erg\ s^{-1}$. It is possible to estimate the size of the region emitting the radiation from the timescale in which the radiation pattern is changing. It turns out that the energy from the quasar is emitted from a very compact region. One can easily show that nuclear fusion cannot be a viable energy source for quasars. It is generally believed that quasars are fuelled by the accretion of matter into a supermassive black hole ($M \approx 10^8 M_\odot$) in the centre of the host galaxy. The friction in the accretion disc causes the matter to lose angular momentum and hence spiral into the black hole; the friction also heats up the disc. Several physical processes transform this heat energy into radiation of different wavelengths. Part of this energy can also come out in the form of long, powerful, jets. The innermost regions of the quasar emit X- and γ-rays. Outer shells emit UV, optical, and radio continuum radiation in the order of increasing radius. Very bright quasars have an apparent magnitude of $m_B \approx 14$ (which corresponds to a flux of $10^{-25}\ erg\ s^{-1}\ cm^{-2}\ Hz^{-1}$) while the faintest ones have $m_B \approx 23$. The absolute magnitudes of the quasars are typically $-30 < M_B < -23$; in contrast, galaxies fall in the band $-23 < M_B < -16$. The relation between m and M for any given quasar depends on the estimated distance to the quasar, which in turn depends on the cosmological model and the quasar's redshift. The luminosity function of the quasars, as a function of their redshift, has been a subject of extensive study. These investigations show that: (i) the space density of bright galaxies (about $10^{-2}\ Mpc^{-3}$) is much higher than that of quasars (about $10^{-5}\ Mpc^{-3}$) with $z < 2$ and (ii) bright quasars were more common in the past ($z \approx 2$) than today ($z \approx 0$). Quasars serve as an important probe of the high redshift universe. Quasars are believed to be one extreme example of a wide class of objects called 'active galaxies'. This term denotes a galaxy which seems to have a very energetic central source of energy. This source is most likely to be a black hole powered by accretion. One kind of active galaxy which has been studied extensively are radio galaxies. The most interesting feature about these radio galaxies is that the radio emission does not arise from the galaxy itself but from two jets of matter extending from the galaxy in opposite directions. It is generally believed that this emission is caused by the synchrotron radiation of relativistic electrons moving in the jets. The moving electrons

generate two elongated clouds containing magnetic fields which, in turn, trap the electrons and lead to the synchrotron radiation.

5.6 Stellar Evolution

The time evolution of a star, which can be depicted as a path in the Hertzsprung-Russell diagram, is quite complicated because of many physical processes which need to be taken into account. Detailed calculations, based on the numerical integration of the relevant differential equations, have provided a fairly comprehensive picture of stellar evolution. One of the primary sources of stellar energy is a series of nuclear reactions converting four protons into a helium nucleus. Since the simultaneous collision of four particles is extremely improbable, this process of converting hydrogen into helium proceeds through two different sequences of intermediate reactions, one called proton-proton chain and the other called carbon-nitrogen-oxygen cycle. In the p-p chain, helium is formed through deuterium and ^3He in the intermediate steps; this reaction is the dominant mechanism for hydrogen-helium conversion at temperatures below $\sim 2 \times 10^7$ K. In the CNO cycle, hydrogen is converted into helium through a sequence of steps involving ^{12}C as a catalyst, i.e., the amount of ^{12}C remains constant at the end of the cycle of reactions. Since the Coulomb barrier for carbon nuclei is quite high, the CNO cycle is dominant only at higher temperature. The evolution of a star like the Sun during the phase of hydrogen-helium conversion, called the 'main sequence' phase, is fairly stable. The stability is essentially due to the following regulatory mechanism: Suppose the temperature decreases slightly causing the nuclear reaction rate to decrease. This will make gravity slightly more dominant, causing a contraction. Once the star contracts, the temperature will again increase, thereby increasing the rate of nuclear reactions and the pressure support. This will restore the balance. After the burning of core hydrogen ends, the core will undergo a contraction, increasing its temperature; if the star now heats up beyond the helium ignition temperature, then the burning of helium will start and stabilize the star. In principle, such a process can continue with the building up of heavier and heavier elements. But to synthesize elements heavier than He is not straight forward because He has a very high binding energy per nucleon among the light elements. Stars achieve synthesis of post-helium elements through a process known as 'triple-alpha reaction' which proceeds as $^4He(^4He,^8Be)\gamma$; $^8Be(^4He,^{12}C)\gamma$. Once ^{12}C has been synthesized, production of heavier elements like ^{16}O, ^{20}Ne, ^{24}Mg etc. can occur through various channels, provided temperatures are high enough, and the star can evolve through successive stages of nuclear burning. The ashes of one stage can become the fuel for the next stage as long as each ignition temperature is reached. Such stars will evolve into structures which contain concentric shells of elements. For example, a $15M_\odot$ star, during its final phase can have layers of iron, silicon, oxygen, neon, carbon, helium, and hydrogen all burning at their inner edges.

The details of the above process, which occurs after the exhaustion of most of the fuel in the core, depend sensitively on the core mass. Consider, for example, a star with $M > 1M_\odot$. Its evolution proceeds in the following manner: Once the hydrogen is exhausted in the core, the core, containing predominantly helium, undergoes gravitational contraction. This increases the temperature of the material just beyond the core and causes renewed burning of hydrogen in

a shell-like region. Soon, the core contracts rapidly, increasing the energy production and the pressure in the shell, thereby causing the outer envelope to expand. Such an expansion leads to the cooling of the surface of the star. About this time, convection becomes the dominant mechanism for energy transport in the envelope and the luminosity of the star increases due to convective mixing. This is usually called the 'red-giant' phase. During the core contraction, the matter gets compressed to very high densities ($\sim 10^5 \ g \ cm^{-3}$) so that it behaves like a degenerate gas and not as an perfect gas. Once the core temperature is high enough to initiate the triple-alpha reaction, helium burning occurs at the core. Since degenerate gas has a high thermal conductivity, this process occurs very rapidly, called 'helium flash'. If the core was dominated by gas pressure, such an explosive ignition would have increased the pressure and led to an expansion; but since the degeneracy pressure is reasonably independent of temperature, this does not happen. Instead the evolution proceeds as a run-away process: The increase in temperature causes an increase in the triple-alpha reaction rate, causing further increase in temperature etc. Finally, when the temperature becomes $\sim 3.5 \times 10^8$ K, the electrons become non-degenerate; the core then expands and cools. The star has now reached a stage with helium burning in the core and hydrogen burning in a shell around the core. Soon the core is mostly converted into carbon and the reaction again stops. The process described above occurs once again, this time with a carbon-rich, degenerate core, and a helium burning shell. This situation, however, turns out to be unstable because the triple-alpha reaction is highly sensitive to temperature. This reaction can over respond to any fluctuations in pressure or temperature thereby causing pulsations of the star with increasing amplitude. Such violent pulsation can eject the cool, outer layers of the star leaving behind a hot core. The ejected envelope becomes what is known as a 'planetary nebula'. The above discussion assumes that the core could contract sufficiently to reach the ignition temperature for carbon burning. In low mass stars, degeneracy pressure stops the star from reaching this phase and it ends up as a 'white dwarf' supported by the degeneracy pressure of electrons against gravity. A more complicated sequence of nuclear burning is possible in stars with $M >> 1 M_\odot$. After the exhaustion of carbon burning in the core, one can have successive phases with neon, oxygen and silicon burning in the core with successive shells of lighter elements around it. This process can proceed until ^{56}Fe is produced in the core.

The binding energy per nucleon is maximum for the ^{56}Fe nucleus; hence it will not be energetically feasible for heavier elements to be synthesized by nuclear fusion. The core now collapses violently reaching very high, about $10^{10}K$, temperatures. The ^{56}Fe photo-disintegrates into alpha particles, and then even the alpha particles disintegrate at such high temperatures to become protons. The collapse of the core squeezes together protons and electrons to form neutrons and the material reaches near-nuclear densities forming a 'neutron star'. There exist several physical processes which can transfer the gravitational energy from core collapse to the envelope, thereby leading to the forceful ejection of the outer envelope causing a 'supernova explosion'. A remnant with smaller mass is left behind. Numerical studies show that stars with $M > 8 M_\odot$ burn hydrogen, helium, and carbon and evolve rather smoothly. During the final phase, such a star explodes as a supernova leaving behind a remnant which could be a white dwarf, neutron star, or black hole. It is generally believed that stars with masses in the intermediate range, $2 M_\odot < M < 8 M_\odot$, do not burn hydrogen and helium in degenerate cores

but evolve through carbon burning in degenerate matter (for $M > 4M_\odot$) ending again in a supernova explosion. Stars with lower mass do not explode but end up as planetary nebulae. Low mass stars with $M < 2M_\odot$ ignite helium in degenerate cores at the tip of the red giant branch and then evolve in a complicated manner. The synthesis of elements as described above proceeds smoothly up to ^{56}Fe. Heavier elements are formed by nuclei absorbing free neutrons, produced in earlier reactions by two different processes called the 'r-process' (rapid neutron capture process) and the 's-process' (slow neutron capture process). During the supernova explosion, a significant part of the heavy elements synthesized in the star will be ejected out into the interstellar space. A second generation of stars can form from these gaseous remnants. The initial composition of material in this second generation will contain a higher proportion of heavier elements (called 'metals') compared to the first generation stars. Both these types of stars are observed in the universe; because of historical reasons, stars in the second generation are called population I stars while those in the first generation are called population II stars.

The above discussion shows how stars could synthesize heavier elements, even if they originally start as gaseous spheres of hydrogen. The study of the spectra of stars allows to determine the relative proportion of various elements present in the stars. Such studies show that population II stars are made of about 75% hydrogen and 25% helium; even population I stars consist of an almost similar proportions of hydrogen and helium with a small percentage of heavier elements ($\sim 2\%$). It is possible to show, using stellar evolution calculations, that it is difficult for the stars to have synthesized elements in such a proportion, if they originally had only hydrogen (called primordial or population III stars). Hence, such a universal composition leads us to conjecture that the primordial gas from which population II stars have formed must have been a mixture of hydrogen and helium in the ratio 3:1 by weight. Heavier elements synthesized by these population II stars would have been dispersed in the interstellar medium by supernova explosions. The population I stars are supposed to have been formed from this medium, containing a trace of heavier elements. The helium present in the primordial gas should have been synthesized at a still earlier epoch, the Big Bang, and cannot be accounted for by stellar evolution. Cosmological models provide an explanation for the presence of this primordial helium.

TABLE 4.

6   MATHEMATICS AND PHYSICS AND THE STRUCTURE OF THE UNIVERSE

6.1   General Relativity and Quantum Field Theory

A mathematician represents the motion of the planets of the solar system by a flow line of an incompressible fluid in a 54-dimensional phase space, whose volume is given by the Liouville measure; while a famous physicist is said to have made the statement that the whole purpose of physics is to find a number, with decimal points, etc.!, otherwise you have not done anything (Manin, 1980). Despite such extreme points of view it can be safely said that the relations

between mathematics and physics (and astronomy) have been very productive in past epochs of the evolution of these disciplines (Barrow and Tipler, 1988).

Mathematical structures entered the development of physics, and problems emanating from physics influenced developments in mathematics. Examples are the role of differential geometry in general relativity, the dynamical theory of space and time, and the influence of quantum mechanics in the development of functional analysis and built on the understanding of Hilbert spaces. A prospective similar development occurred only recently when non-Abelian gauge theories emerged as the quantum field theories for describing fundamental particle interactions. Yang-Mills theory found its mathematical formulation in the theory of principal fiber bundles. The understanding of anomalies in gauge theories involved the theory of families of elliptic operators and representation theory of infinite-dimensional Lie algebras and their cohomologies. Based on these developments, there are two fundamental theories in modern physics: General relativity and quantum field theory. General relativity describes gravitational forces on an astronomical scale. Quantum field theory describes the interaction of fundamental particles, electromagnetism, weak, and strong forces. The formal quantization of general relativity is leading to infinities and the current understanding is that the mathematical machinery is missing to accomplish the unification of general relativity and quantum field theory. More recently attention has turned to the exploration of the mathematical structure of non-Abelian gauge theories and to the more ambitious attempts to construct unified theories of all the fundamental interactions of matter together with gravity. A success of such attempts may reveal new insights for structural elements of the microcosmos and macrocosmos (Schmid, 1992).

6.2 Macroscopic Dimension of Space

Of all the fundamental constants the most familiar one is the dimension of physical space, $N = 3$. Variation of such a fundamental characteristic as the dimension N may lead to unpredictable changes of physical laws. It was Paul Ehrenfest (1880-1933) who, in 1917, was trying to answer the question of why physical space is three-dimensional. From physics, we are familiar with the analogy between Coulomb's law and Newton's law (eqs.(1) and (2)). In both cases, the force is $F \propto r^{-2}$. In physics these laws are treated separately. This lack of coherency obscures a profound relationship of the electromagnetic and the gravitational forces with the properties of space, in particular, with its dimension. Two properties are common to the gravitational and the electromagnetic interactions: Both are weak and long-range. In modern language, this means that the mass of the gauge boson is zero in both cases, implying that the interaction radius is infinite and that the interaction constants are small, α_g, $\alpha_e << 1$ (eqs. (3) and (4)). In the language of physics these properties mean, that the lines of forces, originating at the point where their source is located, run to infinity, not intersecting with each other, provided that no other source is present. The fact that the lines of force extend to infinity reflects the long-range character of the gravitational and electromagnetic forces; the absence of intercepts signifies that there is no reciprocal action between the lines of force, i.e., that the interactions under consideration are weak. The combination of both properties, the weakness and the long-range action, is not characteristic for the other interactions. The force F exerted by one particle on another particle, a distance r apart, is proportional to the density n_i of the lines of force.

Accordingly,

$$F \propto n_i = \frac{f}{4\pi r^2}. \tag{30}$$

The proportionality constant f in (30) is by definition equal to the product of the charges of both particles (Coulomb's law) or of their masses (Newton's law). The denominator in (30) gives the surface area S of a sphere of radius r. For the three-dimensional space, this quantity equals $S_3 = 4\pi r^2 = a_3 r^{3-1}$. These considerations can be repeated for the more general case of an N-dimensional space. The surface area of a sphere in such a space is $S_N = a_N r^{N-1}$. Therefore, the force F_N, acting in an N-dimensional space, is

$$F_N = \frac{b_N}{r^{N-1}}. \tag{31}$$

Accordingly, the potential energy has the form

$$U_N = \frac{-b_N}{[(N-2)r^{N-2}]}, \tag{32}$$

where $N \neq 2$; for $N = 2$, the dependence is logarithmic. It should be stressed that these expressions apply only for integer N, and only for long-range forces in the quasistatic approximation, i.e., for motion in a central force field. The existence of stable orbits in a central force field in an N-dimensional space is determined by (31) and consequently by the dimension N. From mechanics, it is known that the existence of stable orbits depends on the form of the r-dependence of the effective potential

$$U_{Ne} = U_N + \frac{M^2}{2mr^2}, \tag{33}$$

where $M^2/(2mr^2)$ is the centrifugal energy, M the angular momentum, and m the mass of the body moving at a distance r. A stable state is possible if the dependence $U_{Ne}(r)$ has a minimum at a value of r different from zero or infinity. Henceforth the attractive forces are considered for which $U_N < 0$. The results of an analysis of the function $U_{Ne}(r)$ with regard to the existence of an extremum, are the following:

For $N > 4$, the dependence $U_{Ne}(r)$ has a maximum at $r \neq 0$ and a minimum at $r = 0$ which corresponds to merging of the two particles.

For $N = 4$, the dependence $U_{Ne}(r)$ is given by a monotonically decreasing function exhibiting no extrema.

For $N = 2$ and $N = 3$, the function $U_{Ne}(r)$ has a minimum at $r \neq 0$ and $r \neq \infty$.

For $N = 1$, the function $U_{Ne}(r)$ is monotonically increasing.

The existence of a minimum in the dependence $U_{Ne}(r)$ is a necessary condition for the stability of motion. For this reason, the existence and the properties of closed orbits are determined by the dimension of space, N. For $N > 4$, there is no minimum at $r \neq 0, \infty$; consequently there are no stable closed orbits. Any motion, caused by long-range forces would be of one of the following two types: Either it is infinite (the body escapes to infinity) or

otherwise, the moving body falls on a massive central body. At $N = 2$ or $N = 3$, all types of motion are possible: Infinite motion, fall onto a central body and, notably, motion in stable, closed orbits. For $N = 1$, only finite motion is possible; a body cannot escape to infinity. In the one-dimensional case, no orbital motion occurs, and the centrifugal potential is zero ($M = 0$). The effective potential, (32), is then $U_1 = b_1 r$, and the force F_1=const. This corresponds to an infinitely deep potential well. To remove the body from this well, an infinitely large force has to be applied; this means it would be impossible for the body to escape to infinity. Hence, the degree of stability grows as the dimension N decreases. For $N > 4$, there are no analogues to planetary systems. Similar considerations in the framework of quantum mechanics have demonstrated that for $N > 4$, stable atomic systems do not exist, either. It appears that the absence of analogues of planets and atoms for $N > 4$ is a clue to the understanding of the significance of the space dimension $N = 3$, with regard to the existence of structural elements in the universe.

6.3   Microscopic Dimension of Space

In classical physics, particles have definite locations and follow exact trajectories in spacetime. In quantum mechanics, wavepackets propagate through spacetime, their positions and velocities uncertain according to Heisenberg's uncertainty principle. In string theory, point particles are replaced by tiny loops with the result that the concept of spacetime becomes "fuzzy" at scales comparable to the square root of a new fundamental constant, $\alpha' \approx (10^{-32} cm)^2$, introduced as string tension in string theory. Employing both string tension ($\alpha' \neq 0$) and quantum effects ($\hbar \neq 0$) leads to results that may change the conventional notion of spacetime (Donaldson, 1996). The situation of introducing α' in string theory is similar to passing from classical to quantum mechanics by the introduction of Planck's constant $\hbar$. In string theory the one-dimensional trajectory of a particle in spacetime is replaced by a two-dimensional orbit of a string. According to Heisenberg's uncertainty principle, at a momentum p one can probe a distance $x \approx \hbar/p$. However, the introduction of $\alpha's$ acts, as if Heisenberg's uncertainty principle would have two terms, $\Delta x \geq \hbar/\Delta p + \alpha'(\Delta p/\hbar)$, where the second term reflects the fuzziness due to string theory. Then, the constant α' would be the absolute minimum uncertainty in length in any physical experiment. The consequences of this type of quantum field theory for fundamental particles and the structure of the universe are still to be discovered.

GLOSSARY (of terms related to the principal structural elements of the universe)

Antiparticle: A particle of opposite charge but otherwise identical to its partner. Most of the observable universe consists of particles and matter, as opposed to antiparticles and antimatter.

Asteroids: Small planetlike bodies of the solar system.

Atom: The basic building block of matter. Each atom consists of a nucleus with positive electric charge and a surrounding cloud of electrons with negative charge.

Baryon: Type of hadron, consisting of proton, neutron, and the unstable hyperons (and their antiparticles).

Binary System: A system of two objects orbiting around a common center. The objects may be stars or black holes or a star and a black hole.

Black Hole: A region in which matter has collapsed to such an extend that light can no longer escape from it.

Boson: A class of particles with integer units of the basic unit of spin $h/2\pi$.

Cluster of Galaxies: An aggregate of galaxies. Clusters may range in richness from loose groups, such as the Local Group, with 10 to 100 members, to great clusters of over 1000 galaxies.

Cluster of Stars (Globular Star Cluster): An aggregate of stars. Globular star clusters contain the oldest stars in the galaxy and high-velocity stars.

Comet: A diffuse body of gas and solid particles that orbit the Sun in a highly eccentric trajectory.

Cosmic Microwave Background Radiation: Diffuse isotrope radiation whose spectrum is that of a blackbody at 3 degrees kelvin and consequently is most intense in the microwave region of the spectrum.

Cosmic String: A hypothetical one-dimensional, string-like object that is made from a curvature of space.

Cosmogony: The study of the origin of celestial systems, ranging from the solar system to stars, galaxies, and clusters of galaxies.

Cosmology: The study of the large-scale structure and evolution of the universe.

Dark Matter: Matter whose presence is inferred from dynamical measurements but which has no optical counterpart.

Electron: A particle of matter with negative electric charge. All chemical properties of atoms and molecules are determined by the electrical interactions of electrons with each other and with the atomic nuclei.

Fermion: A particle with half integral units of the basic unit of spin, $h/2\pi$.

Galactic Nucleus: Innermost region of a galaxy exhibiting a concentration of stars and gas.

Galaxy: A large gravitationally bound cluster of stars that all orbit around a common center. Galaxies are basic building blocks of the universe.

Graviton: The particle which, according to wave-particle duality, is associated with gravitational waves.

Group of Galaxies: Gravitationally bound system of few galaxies.

Group of Stars: Gravitationally bound system of few stars (multiple stars).

HI Cloud: Cloud of cool, neutral hydrogen.

HII Region: Cloud of hot, ionized hydrogen, usually heated by a massive young hot star.

Hadron: Particle (protons, neutrons, mesons) which takes part in strong nuclear reactions.

Halo: The diffuse, nearly spherical cloud of old stars and globular clusters that surrounds a spiral galaxy.

Hertzsprung-Russell Diagram: Plot of stellar luminosity (or absolute magnitude) against effective temperature (or color), in which the evolution of stars of different masses may be followed.

Hubble Classification of Galaxies: Organizes galaxies according to shape. They range from amorphous, relatively uniform elliptical systems to highly flattened spiral disks with prominent nuclei. It is not a classification based on evolution but one of different rates of star formation.

Hypergalaxy: A system consisting of a dominant spiral galaxy surrounded by a cloud of dwarf satellite galaxies, often ellipticals. The Milky Way and the Andromeda galaxy are hypergalaxies.

Irregular Galaxy: A galaxy without spiral structure or smooth, spheroidal shape, often filamentary or very clumpy, and generally of low mass (10^7 to $10^{10} M\odot$).

Intergalactic Gas: Matter that is present in the region between galaxies. It has been detected in considerable amounts in great clusters of galaxies, where the intergalactic gas is so hot that it emits copious amounts of x- rays.

Interstellar Grains: Small needle-shaped particles in the interstellar gas with dimensions from 10^{-6} to 10^{-5} cm. They are primarily composed of silicates and strongly absorb, scatter, and polarize visible light in the far-infrared region of the spectrum.

Lepton: Particles (neutrinos, electrons, muons) which do not take part in strong interactions.

Local Group: Small group of 30 or so galaxies of which the Milky Way and the Andromeda galaxy are the two dominant members.

Meson: A class of strongly interacting particles with zero baryon number, among them the pi meson.

Meteorites: A solid portion of a meteoroid that has reached the Earth's surface.

Molecular Cloud: An interstellar cloud consisting predominantly of molecular hydrogen, with trace amounts of other molecules such as carbon monoxide and ammonia.

Molecule: An entity made of several atoms that share their electron clouds with each other.

Neutrino: A particle that resembles the photon, except that it interacts weakly with matter. Neutrinos come in at least three varieties, known as electron-type, muon-type, and tauon-type.

Neutron: The uncharged particle found along with protons in atomic nuclei.

Neutron Star: Cold, degenerate, compact star in which nuclear fuels have been exhausted and pressure support against gravity is provided be the pressure of neutrons.

Nucleon: Nuclear particles, i.e. neutrons and protons.

Observable Universe: The extend of the universe that we can see with the aid of large telescopes. Its ultimate boundary is determined by the horizon size.

Photon: A discrete unit of electromagnetic energy. The particle which, according to wave-particle duality, is associated with electromagnetic energy.

Positron: The antiparticle of an electron, having positive charge but being otherwise similar.

Proton: The positively charged particle found along with neutrons in atomic nuclei

Pulsar: A magnetized, spinning neutron star that emits a beam of radiation; radio waves and sometimes also light and X-rays).

Quark: Particles of which all hadrons are supposed to be composed.

Quasar: Luminous and compact quasi-stellar radio source related to violent events in the nuclei of a galaxy, believed to be powered by a massive black hole.

Red Giant: Phase in star's evolution after completion of hydrogen burning when outer layers become very extended.

Spiral Galaxy: A galaxy with a prominent nuclear bulge and luminous spiral arms of gas, dust, and young stars that wind out from the nucleus.

Star: Stars are basic building blocks of the universe.

Supercluster: A cluster of clusters of galaxies.

Universe: Our universe.

White Dwarf: Cool, degenerate, compact star, in which nuclear fuels are exhausted and pressure support against gravity is provided by the degeneracy pressure of electrons.

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Figure Captions

Fig.1. It must be related to geometry and it may have been a window to the stars. Stonehenge in Wiltshire, England, still the focus of hot debates.

Fig.2. Shiva is one of the two pricipal Hindu gods (the other being Vishnu); his most celebrated appearance being the one as Nataraja, the King of Dancers. Indian artists have represented Shiva's cosmic dance in magnificent brone sculptures of dancing figures with four arms whose superbly balanced and yet dynamic gestures express the rhythm and unity of life. The upper right hand of the god holds a drum to symbolize the primal sound of creation, the upper left bears a tongue of flame, the element of destruction. The balance of the two hands represents the dynamic balance of creation and destruction in the univese, accenturated further by the Dancer's calm and detached face in the centre of the two hands, in which the polarity of creation and destruction is dissolved and transcended. The second right hand is raised in the sign of 'do not fear', symbolizing maintenance, protection and peace, while the remaining left hand points down to the uplifted foot which symbolizes release from the spell of maya. The god is pictured as dancing on the body of a demon, the symbol of human ignorance which has to be conquered befor liberation can be attained.

Fig.3. Dante Alighieri's (1265-1321) scheme of the Universe in illustration from "Paradies" in "The Divine comedy" extends Aristotelian cosmology in a modern way. Dante traverses the material world from the icy core of Earth, the abode of Lucifer, to the Mount of Purgatory. He continues through the nine heavenly spheres, each sphere larger and more rapidly turning than the last, until he reaches the Primum Mobile, the ninth and largest sphere and the boundary of space. His goal was to see the Empyrean, the abode of God.

Fig.4. The first diagram to illustrate the proposal that the Universe is infinite. From the edition by Thomas Digges of his father's A Prognostication everlastinge..., published in 1576 in London, eight years before its publication by Giordano Bruno to whom the idea is often credited (By permission of The Royal Society).

Fig.5. The continuum of size and organizational level appears throughout the range of structural elements, from the fundamental particles to the highest-level systems of matter. Particles such as the quarks are known to be bound by strong forces. Protons and neutrons are bound within the atomic nucleus. The outer shell of atoms is bound to the nucleus by electromagnetic forces. A molecule may be thought of either as a structure build of atoms bound together by chemical forces or as a structure in which two or more nuclei are maintained in some definite geometrical configuration by attractive forces from a surrounding cloud of negative electrons. The evolution of the universe created a hierarchy of structural elements.

Fig.6. The Big Bang: From the origin of the universe to its present epoch (Smoot and Davidson, 1995).

Fig.7. Cosmology has been actively investigating the consequences of a new extension of the theory of matter within the evolution of the universe, in which the electricity, magnetism, weak force, strong force, and gravity are all unified at sufficiently high temperatures.

Fig.8. Three full-sky maps made by the COBE satellite DMR instrument show (Smoot and Davidson, 1995).
Top: The dipole anisotropy caused by the Earth's motion relative to the cosmic background radiation (hotter in the direction we are going, cooler in the direction we are leaving).
Center: The dipole-removed sky showing the emission from the plane of the galaxy - the horizontal red strip and the large-scale ripples in space-time.
Bottom: A map of the wrinkles in time.

Fig.9. The Big Bang, with inflation producing space and the ripples in space-time mapped by COBE, and eventually evolving to become stars and galaxies and clusters of them (Smoot and Davidson, 1995).

Fig.10. A map of the nearby universe toward the north and south poles of the Milky Way. Each of the 9325 points in the image represents a galaxy similar to the Milky Way. The arcs which form the boundaries of the two wedge-like portions of the map are all at a distance of about 400 million light years from the Sun (Earth). The dark regions to the east and west are obscured by the plane of the Milky Way. The map shows that galaxies are arranged in patterns on an enormous scale. The Great Wall, a sheet containing thousands of galaxies, stretches nearly horizontally across the entire northern portion of the survey. A similar Southern Wall runs diagonally across the southern region. These walls delineate enormous dark voids where there are few if any galaxies. The voids are often 150 million light years in diameter. The patterns in the north and south are similar. These large patterns are a tough challenge for our attempts to model the development of structure in the universe. The curved boundaries are lines of constant declination (Galactic latitude): in the north they are at 8.5^o and 44.5^o (the wedge subtends an angle of 36° in the narrow direction). It runs from 8 to 17 hours in right ascension (longitude) or of order 120°. In the south the declination runs from 0° to -40° and the right ascension runs from 20.8 to 4 hours.
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Table 1. Fundamental fermions divided into two groups: leptons and quarks (Barnett et al., 1996).

LEPTONS spin=1/2						
Electric charge	Flavor	Mass GeV/c^2	Flavor	Mass GeV/c^2	Flavor	Mass GeV/c^2
0	ν_e electron neutrino	$< 1 \times 10^{-8}$	ν_μ muon neutrino	1.7×10^{-4}	ν_τ tau neutrino	$< 2.4 \times 10^{-3}$
-1	e electron	5.1×10^{-4}	μ muon	0.106	τ tau	1.777
QUARKS spin=1/2						
Electric charge	Flavor	Approx. mass GeV/c^2	Flavor	Approx. mass GeV/c^2	Flavor	Approx. mass GeV/c^2
2/3	**u** up	$(2-8) \times 10^{-3}$	**c** charm	1-1.6	**t** top	180
-1/3	**d** down	$(5-15) \times 10^{-3}$	**s** strange	0.1-0.3	**b** bottom	4.1-4.5

BOSONS spin = 0,1,2,...				
Unified **Elektroweak** spin = 1	γ photon	W^-	W^+	Z^0
Electric charge	0	-1	+1	0
Mass Gev/c^2	0	80	80	91
Strong or Color spin = 1	g gluon			
electric charge	0			
Mass GeV/c^2	0			

Table 2. Properties of the force carrriers (Barnett et al., 1996).

Interaction	Coupling constant		Interaction
	Analytic expression	Numerical value at $m = m_p$	Radius cm
Gravitational	$Gm^2/\hbar c$	$\sim 10^{-38}$	∞
Weak	$g_F m^2 c/\hbar^3$	10^{-5}	10^{-17}
Electromagnetic	$e^2/\hbar c$	$1/137$	∞
Strong	$a/[ln(m/m_p)]$ $m >> m_p$	≈ 1	10^{-13}

Table 3. Properties of the four fundamental interactions

Object	Mass	Radius
	g	cm
jupiter	2×10^{30}	6×10^9
sun	2×10^{33}	7×10^{10}
red giant	$(2-6) \times 10^{34}$	10^{14}
white dwarf	2×10^{33}	10^8
neutron star	3×10^{33}	10^6
glob. cluster	1.2×10^{39}	1.5×10^{20}
open cluster	5×10^{35}	3×10^{19}
spiral	$2 \times (10^{44} - 10^{45})$	$(6-15) \times 10^{22}$
elliptical	$2 \times (10^{43} - 10^{45})$	$(1.5-3) \times 10^{23}$
group	4×10^{46}	3×10^{24}
cluster	2×10^{48}	1.2×10^{25}

Table 4. Structural elements of the universe