

Chapter 1

Understanding the Universe: Cosmology, Astrophysics, Particles, and Their Interactions



Cosmology, astrophysics, and the physics of elementary particles and interactions are intimately connected. After reading this chapter, it will be clear that these subjects are part of the same field of investigation: this book will show you some of the connections, and maybe many more you will discover yourself in the future.

1.1 Particle and Astroparticle Physics

The Universe around us, the objects surrounding us, display an enormous diversity. Is this diversity built over small hidden structures? This interrogation started out, as it often happens, as a philosophical question, only to become, several thousand years later, a scientific one. In the sixth and fifth century BC in India and Greece the atomic concept was proposed: matter was formed by small, invisible, indivisible, and eternal particles: the atoms—a word invented by Leucippus (460 BC) and made popular by his disciple Democritus. In the late eighteenth and early nineteenth century, chemistry gave finally to atomism the status of a scientific theory (mass conservation law, Lavoisier 1789; ideal gas laws, Gay-Lussac 1802; multiple proportional law, Dalton 1805), which was strongly reinforced with the establishment of the periodic table of elements by Mendeleev in 1869—the chemical properties of an element depend on a “magic” number, its atomic number.

If atoms did exist, their shape and structure were to be discovered. For Dalton, who lived before the formalization of electromagnetism, atoms had to be able to establish mechanical links with each other. After Maxwell (who formulated the electromagnetic field equations) and J.J. Thomson (who discovered the electron) the binding force was supposed to be the electric one and in atoms an equal number of positive and

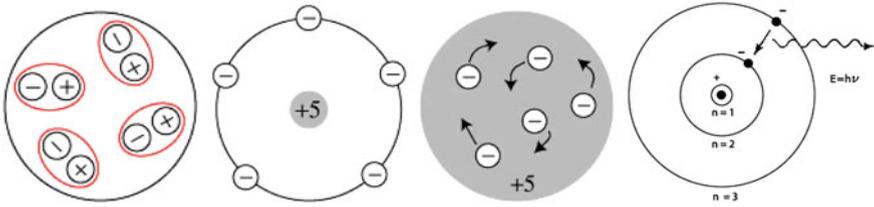


Fig. 1.1 Sketch of the atom according to atomic models by several scientists in the early twentieth century: from left to right, the Lenard model, the Nagaoka model, the Thomson model, and the Bohr model with the constraints from the Rutherford experiment. Source: <http://skullsinthestars.com/2008/05/27/the-gallery-of-failed-atomic-models-1903-1913>

negative electric charges had to be accommodated in stable configurations. Several solutions were proposed (Fig. 1.1), from the association of small electric dipoles by Philip Lenard (1903) to the Saturnian model of Hantora Nagaoka (1904), where the positive charges were surrounded by the negative ones like the planet Saturn and its rings. In the Anglo-Saxon world the most popular model was, however, the so-called plum pudding model of Thomson (1904), where the negative charges, the electrons, were immersed in a “soup” of positive charges. This model was clearly dismissed by Rutherford, who demonstrated in the beginning of the twentieth century that the positive charges had to be concentrated in a very small nucleus.

Natural radioactivity was the first way to investigate the intimate structure of matter; then people needed higher energy particles to access smaller distance scales. These particles came again from natural sources: it was discovered in the beginning of the twentieth century that the Earth is bombarded by very high-energy particles coming from extraterrestrial sources. These particles were named “cosmic rays.” A rich and not predicted spectrum of new particles was discovered. Particle physics, the study of the elementary structure of matter, also called “high-energy physics,” was born.

High-energy physics is somehow synonymous with fundamental physics. The reason is that, due to Heisenberg’s¹ principle, the minimum scale of distance Δx we can sample is inversely proportional to the momentum (which approximately equals the ratio of the energy E by the speed of light c for large energies) of the probe we are using for the investigation itself:

$$\Delta x \simeq \frac{\hbar}{\Delta p} \simeq \frac{\hbar}{p}.$$

¹Werner Heisenberg (1901–1976) was a German theoretical physicist and was awarded the 1932 Nobel Prize in Physics “for the creation of quantum mechanics.” He also contributed to the theories of hydrodynamics, ferromagnetism, cosmic rays, and subatomic physics. During World War II he worked on atomic research, and after the end of the war he was arrested, then rehabilitated. Finally he organized the Max Planck Institute for Physics, which is named after him.

In the above equation, $\hbar = h/2\pi \simeq 10^{-34}$ J s is the so-called Planck² constant (sometimes the name of Planck constant is given to h). Accelerating machines, developed in the mid-twentieth century, provided higher and higher energy particle beams in optimal experimental conditions. The collision point was well-defined and multilayer detectors could be built around it. Subnuclear particles (quarks) were discovered, and a “standard model of particle physics” was built, piece by piece, until its final consecration with the recent discovery of the Higgs boson. The TeV energy scale (that corresponds to distances down to 10^{-19} – 10^{-20} m) is, for the time being, understood.

However, at the end of the twentieth century, the “end of fundamental physics research” announced once again by some, was dramatically dismissed by new and striking experimental evidence which led to the discovery of neutrino oscillations, which meant nonzero neutrino mass, and by the proof that the Universe is in a state of accelerated expansion and that we are immersed in a dark Universe composed mainly of dark matter and dark energy—whatever those entities, presently unknown to us, are. While the discovery that neutrinos have nonzero mass could be incorporated in the standard model by a simple extension, the problems of dark matter and dark energy are still wide open.

The way to our final understanding of the fundamental constituents of the Universe, which we think will occur at energies of 10^{19} GeV (the so-called Planck scale), is hopelessly long. What is worse, despite the enormous progress made by particle acceleration technology, the energies we shall be able to reach at Earth will always be lower than those of the most energetic cosmic rays—particles reaching the Earth from not yet understood extraterrestrial accelerators. These high-energy beams from space may advance our knowledge of fundamental physics and interactions, and of astrophysical phenomena; last but not least, the messengers from space may advance our knowledge of the Universe on a large scale, from cosmology to the ultimate quest on the origins of life, astrobiology. That is the domain and the ambition of the new field of fundamental physics called astroparticle physics. This book addresses this field.

Let us start from the fundamental entities: particles and their interactions.

1.2 Particles and Fields

The paradigm which is currently accepted by most researchers, and which is at the basis of the so-called standard model of particle physics, is that there is a set of elementary particles constituting matter. From a philosophical point of view, even the very issue of the existence of elementary particles is far from being established:

²Max Planck (1858–1934) was the originator of quantum theory, and deeply influenced the human understanding of atomic and subatomic processes. Professor in Berlin, he was awarded the Nobel Prize in 1918 “in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta.” Politically aligned with the German nationalistic positions during World War I, Planck was later opposed to Nazism. Planck’s son, Erwin, was arrested after an assassination attempt of Hitler and died at the hands of the Gestapo.

the concept of elementarity may just depend on the energy scale at which matter is investigated—i.e., ultimately, on the experiment itself. And since we use finite energies, a limit exists to the scale one can probe. The mathematical description of particles, in the modern quantum mechanical view, is that of fields, i.e., of complex amplitudes associated to points in spacetime, to which a local probability can be associated.

Interactions between elementary particles are described by fields representing the forces; in the quantum theory of fields, these fields can be seen as particles themselves. In classical mechanics fields were just a mathematical abstraction; the real thing were the forces. The paradigmatic example was Newton's³ instantaneous and universal gravitation law. Later, Maxwell gave to the electromagnetic field the status of a physical entity: it transports energy and momentum in the form of electromagnetic waves and propagates at a finite velocity—the speed of light. Then, Einstein⁴ explained the photoelectric effect postulating the existence of photons—the interaction of the electromagnetic waves with free electrons, as discovered by Compton,⁵ was equivalent to elastic collisions between two particles: the photon and the electron. Finally with quantum mechanics the wave-particle duality was extended to all “field” and “matter” particles.

Field particles and matter particles have different behaviors. Whereas matter particles comply with the Pauli⁶ exclusion principle—only one particle can occupy a given quantum state (matter particles obey Fermi-Dirac statistics and are called

³Sir Isaac Newton (1642–1727) was an English physicist, mathematician, astronomer, alchemist, and theologian, who deeply influenced science and culture down to the present days. His monograph *Philosophiæ Naturalis Principia Mathematica* (1687) provided the foundations for classical mechanics. Newton built the first reflecting telescope and developed theories of color and sound. In mathematics, Newton developed differential and integral calculus (independently from Leibnitz). Newton was also deeply involved in occult studies and interpretations of religion.

⁴Albert Einstein (1879–1955) was a German-born physicist who deeply changed the human representation of the Universe, and our concepts of space and time. Although he is best known by the general public for his theories of relativity and for his mass-energy equivalence formula $E = mc^2$ (the main articles on the special theory of relativity and the $E = mc^2$ articles were published in 1905), he received the 1921 Nobel Prize in Physics “especially for his discovery of the law of the photoelectric effect” (also published in 1905), which was fundamental for establishing quantum theory. The young Einstein noticed that Newtonian mechanics could not reconcile the laws of dynamics with the laws of electromagnetism; this led to the development of his special theory of relativity. He realized, however, that the principle of relativity could also be extended to accelerated frames of reference when one was including gravitational fields, which led to his general theory of relativity (1916). A professor in Berlin, he moved to the USA when Adolf Hitler came to power in 1933, becoming a US citizen in 1940. During World War II, he cooperated with the Manhattan Project, which led to the atomic bomb. Later, however, he took a position against nuclear weapons. In the USA, Einstein was affiliated with the Institute for Advanced Study in Princeton.

⁵Arthur H. Compton (1892–1962) was awarded the Nobel Prize in Physics in 1927 for his 1923 discovery of the now-called Compton effect, which demonstrated the particle nature of electromagnetic radiation. During World War II, he was a key figure in the Manhattan Project. He championed the idea of human freedom based on quantum indeterminacy,

⁶Wolfgang Ernst (the famous physicist Ernst Mach was his godfather) Pauli (Vienna, Austria, 1900—Zurich, Switzerland, 1958) was awarded the 1945 Nobel prize in physics “for the discovery of the exclusion principle, also called the Pauli principle.” He also predicted the existence of neutrinos. Professor in ETH Zurich and in Princeton, he had a rich exchange of letters with psychologist Carl

“fermions”)—there is no limit to the number of identical and indistinguishable field particles that can occupy the same quantum state (field particles obey Bose–Einstein statistics and are called “bosons”). Lasers (coherent streams of photons) and the electronic structure of atoms are thus justified. The spin of a particle and the statistics it obeys are connected by the spin-statistics theorem: according to this highly nontrivial theorem, demonstrated by Fierz (1939) and Pauli (1940), fermions have half-integer spins, whereas bosons have integer spins.

At the present energy scales and to our current knowledge, there are 12 elementary “matter” particles; they all have spin $1/2$, and hence, they are fermions. The 12 “matter particles” currently known can be divided into two big families: 6 leptons (e.g., the electron, of charge $-e$, and the neutrino, neutral), and 6 quarks (a state of 3 bound quarks constitutes a nucleon, like the proton or the neutron). Each big family can be divided into three generations of two particles each; generations have similar properties—but different masses. This is summarized in Fig. 1.2. A good scale for masses is one GeV/c^2 , approximately equal to 1.79×10^{-27} kg—we are implicitly using the relation $E = mc^2$; the proton mass is about $0.938 \text{ GeV}/c^2$. Notice, however, that masses of the elementary “matter” particles vary by many orders of magnitude, from the neutrino masses which are of the order of a fraction of eV/c^2 , to the electron mass (about half a MeV/c^2), to the top quark mass (about $173 \text{ GeV}/c^2$). Quarks have fractional charges with respect to the absolute value of the electron charge, e : $\frac{2}{3}e$ for the up, charm, top quark, and $-\frac{1}{3}e$ for the down, strange, bottom. Quark names are just fantasy names.

The material constituting Earth can be basically explained by only three particles: the electron, the up quark, and the down quark (the proton being made of two up quarks and one down, uud , and the neutron by one up and two down, udd).

For each known particle there is an antiparticle (antimatter) counterpart, with the same mass and opposite charge quantum numbers. To indicate antiparticles, the following convention holds: if a particle is indicated by P , its antiparticle is in general written with a bar over it, i.e., \bar{P} . For example, to every quark, q , an antiquark, \bar{q} , is associated; the antiparticle of the proton p (uud) is the antiproton \bar{p} ($\bar{u}\bar{u}\bar{d}$), with negative electric charge. The antineutron \bar{n} is the antiparticle of the neutron (note the different quark composition of the two). To the electron neutrino ν_e an anti-electron neutrino $\bar{\nu}_e$ corresponds (we shall see later in the book that neutrinos, although electrically neutral, have quantum numbers allowing them to be distinguished from their antiparticles). A different naming convention is used in the case of the anti-electron or positron e^+ : the superscript denoting the charge makes explicit the fact that the antiparticle has the opposite electric charge to that of its associated particle. The same applies to the heavier leptons (μ^\pm, τ^\pm) and to the “field particles” W^\pm .

At the current energy scales of the Universe, particles interact via four fundamental interactions. There are indications that this view is related to the present-day energy of the Universe: at higher energies—i.e., earlier epochs—some interactions would “unify” and the picture would become simpler. In fact, theorists think that these

Gustav Jung. According to anecdotes, Pauli was a very bad experimentalist, and the ability to break experimental equipment simply by being in the vicinity was called the “Pauli effect.”

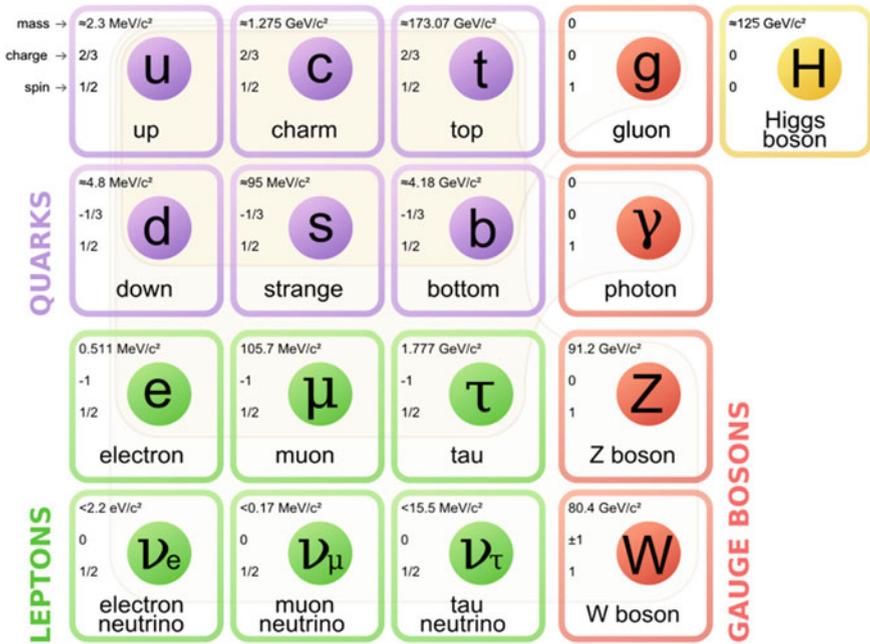


Fig. 1.2 Presently observed elementary particles. Fermions (the matter particles) are listed in the first three columns; gauge bosons (the field particles) are listed in the fourth column. The Higgs boson is standing alone. Adapted from MissMJ [CC BY 3.0 (<http://creativecommons.org/licenses/by/3.0>)], via Wikimedia Commons

interactions might be the remnants of one single interaction that would occur at extreme energies—e.g., the energies typical of the beginning of the Universe. By increasing order of strength:

1. The gravitational interaction, acting between whatever pair of bodies and dominant at macroscopic scales.
2. The electromagnetic interaction, acting between pairs of electrically charged particles (i.e., all matter particles, excluding neutrinos).
3. The weak interaction, also affecting all matter particles (with certain selection rules) and responsible, for instance, for the beta decay and thus for the energy production in the Sun.
4. The color force, acting among quarks. The strong interaction,⁷ responsible for binding the atomic nuclei (it ensures electromagnetic repulsion among protons

⁷This kind of interaction was first conjectured and named by Isaac Newton at the end of the seventeenth century: “There are therefore agents in nature able to make the particles of bodies stick together by very strong attractions. And it is the business of experimental philosophy to find them out. Now the smallest particles of matter may cohere by the strongest attractions and compose bigger particles of weaker virtue; and many of these may cohere and compose bigger particles whose virtue is still weaker, and so on for diverse successions, until the progression ends in the biggest particles on which the operations in chemistry, and the colors of natural bodies depend.” (I. Newton, Opticks).

in nuclei does not break them up) and for the interaction of cosmic protons with the atmosphere, is just a residual shadow (à la van der Waals) of the very strong interaction between quarks.

The relative intensity of such interactions spans many orders of magnitude. In a ${}^2\text{H}$ atom, in a scale where the intensity of strong interactions between the nucleons is 1, the intensity of electromagnetic interactions between electrons and the nucleus is 10^{-5} , the intensity of weak interactions is 10^{-13} , and the intensity of gravitational interactions between the electron and the nucleus is 10^{-45} . However, intensity is not the only relevant characteristic in this context: one should consider also the range of the interactions and the characteristics of the charges. The weak and strong interactions act at subatomic distances, smaller than ~ 1 fm, and they are not very important at astronomical scales. The electromagnetic and gravitational forces have instead a $1/r^2$ dependence. On small (molecular) scales, gravity is negligible compared to electromagnetic forces; but on large scales, the universe is electrically neutral, so that electrostatic forces become negligible. Gravity, the weakest of all forces from a particle physics point of view, is the force determining the evolution of the Universe at large scales.

In the quantum mechanical view of interactions, the interaction itself is mediated by quanta of the force field.

Quanta of the interaction fields	
Strong interaction	Eight gluons
Electromagnetic interaction	Photon (γ)
Weak interaction	Bosons W^+ , W^- , Z
Gravitational interaction	Graviton (?)

According to most scientists, the gravitational interaction is mediated by the graviton, an electrically neutral boson of mass 0 and spin 2, yet undiscovered. The weak interaction is mediated by three vectors: two are charged, the W^+ (of mass $\sim 80.4 \text{ GeV}/c^2$) and its antiparticle, the W^- ; one is neutral, the Z (with mass $\sim 91.2 \text{ GeV}/c^2$). The electromagnetic interaction is mediated by the well-known photon. The color interaction is exchanged by eight massless neutral particles called gluons. The couplings of each particle to the boson(s) associated to a given interaction are determined by the strength of the interaction and by “magic” numbers, called charges. The gravitational charge of a particle is proportional to its mass (energy); the weak charge is the weak isospin charge ($\pm 1/2$ for the fermions sensitive to the weak interaction, 0, ± 1 for bosons); the electrical charge is the well-known (positive and negative) charge; the strong charge comes in three types designated by color names (red, green, blue). Particles or combinations of particles can be neutral to the electromagnetic, weak or strong interaction, but not to the gravitational interaction. For instance, electrons have electric and weak charges but no color charge, and atoms are electrically neutral. At astrophysical scales, the dominant interaction is gravitation; at atomic scales, $\mathcal{O}(1 \text{ nm})$, it is the electromagnetic interaction; and at the scale of nuclei, $\mathcal{O}(1 \text{ fm})$, it is the strong interaction.

In quantum physics the vacuum is not empty at all. Heisenberg's uncertainty relations allow energy conservation violations by a quantity ΔE within small time intervals Δt such that $\Delta t \simeq \hbar/\Delta E$. Massive particles that live in such tiny time intervals are called "virtual." But, besides these particles which are at the origin of measurable effects (like the Casimir effect, see Chap. 6), we have just discovered that space is filled by an extra field to which is associated the Higgs boson, a neutral spinless particle with mass about $125 \text{ GeV}/c^2$. Particles in the present theory are intrinsically massless, and it is their interaction with the Higgs field that originates their mass: the physical properties of particles are related to the properties of the quantum vacuum.

1.3 The Particles of Everyday Life

As we have seen, matter around us is essentially made of atoms; these atoms can be explained by just three particles: protons and neutrons (making up the atomic nuclei) and electrons. Electrons are believed to be elementary particles, while protons and neutrons are believed to be triplets of quarks – uud and udd , respectively. Particles made of triplets of quarks are called baryons. Electrons and protons are stable particles to the best of our present knowledge, while neutrons have an average lifetime (τ) of about 15 min if free, and then they decay, mostly into a proton, an electron and an antineutrino—the so-called β decay. Neutrons in atoms, however, can be stable: the binding energy constraining them in the atomic nucleus can be such that the decay becomes energetically forbidden.

Baryons are not the only allowed combination of quarks: notably, mesons are allowed combinations of a quark and an antiquark. All mesons are unstable. The lightest mesons, called pions, are combinations of u and d quarks and their antiparticles; they come in a triplet of charge (π^+ , π^- , π^0) and have masses of about $0.14 \text{ GeV}/c^2$. Although unstable ($\tau_{\pi^\pm} \simeq 26 \text{ ns}$, mostly decaying through $\pi^+ \rightarrow \mu^+ \nu_\mu$ and similarly for π^- ; $\tau_{\pi^0} \simeq 10^{-16} \text{ s}$, mostly decaying through $\pi^0 \rightarrow \gamma\gamma$), pions are also quite common, since they are one of the final products of the chain of interactions of particles coming from the cosmos (cosmic rays, see later) with the Earth's atmosphere.

All baryons and mesons (i.e., hadrons) considered up to now are combinations of u and d quarks and of their antiparticles. *Strange* hadrons (this is the term we use for baryons and mesons involving the s , or *strange*, quark) are less common, since the mass of the s is larger and the lifetimes of strange particles are of the order of 1 ns. The lightest strange mesons are called the K mesons, which can be charged (K^+ , K^-) or neutral; the lightest strange baryon (uds) is called the Λ .

The heavier brothers of the electrons, the muons (with masses of about $0.11 \text{ GeV}/c^2$), are also common, since they have a relatively long lifetime ($\tau_{\mu^\pm} \simeq 2.2 \mu\text{s}$) and they can propagate for long distances in the atmosphere. They also appear in the chain of interactions/decays of the products of cosmic rays.

Last but not least, a “field particle” is fundamental for our everyday life: the quantum of electromagnetic radiation, the photon (γ). The photon is massless to the best of our knowledge, and electrically neutral. Photon energies are related to their wavelength λ through $E = hc/\lambda$, and the photons of wavelengths between about 0.4 and 0.7 μm can be perceived by our eyes as light.

1.4 The Modern View of Interactions: Quantum Fields and Feynman Diagrams

The purpose of physics is to describe (and possibly predict) change with time. A general concept related to change is the concept of interaction, i.e., the action that occurs as two or more objects have an effect upon one another. Scattering and decay are examples of interactions, leading from an initial state to a final state. The concept of interaction is thus a generalization of the concept of force exchange in classical physics.

Quantum field theories (QFT), which provide in modern physics the description of interactions, describe nature in terms of fields, i.e., of wavefunctions defined in spacetime. A force between two particles (described by “particle fields”) is described in terms of the exchange of virtual force carrier particles (again described by appropriate fields) between them. For example, the electromagnetic force is mediated by the photon field; weak interactions are mediated by the Z and W^\pm fields, while the mediators of the strong interaction are called gluons. “Virtual” means that these particles can be off-shell; i.e., they do not need to have the “right” relationship between mass, momentum, and energy—this is related to the virtual particles that we discussed when introducing the uncertainty relations, which can violate energy–momentum conservation for short times.

Feynman diagrams are pictorial representations of interactions, used in particular for interactions involving subatomic particles, introduced by Richard Feynman⁸ in the late 1940s.

The orientation from left to right in a Feynman diagram normally represents time: an interaction process begins on the left and ends on the right. Basic fermions are represented by straight lines with possibly an arrow to the right for particles, and to the left for antiparticles. Force carriers are represented typically by wavy lines

⁸Richard Feynman (New York 1918–Los Angeles 1988), longtime professor at Caltech, is known for his work in quantum mechanics, in the theory of quantum electrodynamics, as well as in particle physics; he participated in the Manhattan project. In addition, he proposed quantum computing. He received the Nobel Prize in Physics in 1965 for his “fundamental work in quantum electrodynamics, with deep-plowing consequences for the physics of elementary particles.” His life was quite adventurous, and full of anecdotes. In the divorce file related to his second marriage, his wife complained that “He begins working calculus problems in his head as soon as he awakens. He did calculus while driving in his car, while sitting in the living room, and while lying in bed at night.” He wrote several popular physics books, and an excellent general physics textbook now freely available at <http://www.feynmanlectures.caltech.edu/>.

(photons), springs (gluons), dashed lines (W^\pm and Z). Two important rules that the Feynman diagrams must satisfy clarify the meaning of such representation:

- conservation of energy and momentum is required at every vertex;
- lines entering or leaving the diagram represent real particles and must have $E^2 = p^2c^2 + m^2c^4$ (see in the next chapter the discussion on Einstein’s special relativity).

Associated with Feynman diagrams are mathematical rules (called the “Feynman rules”) that enable the calculation of the probability (quantum mechanically, the square of the absolute value of the amplitude) for a given reaction to occur; we shall describe the quantitative aspects in larger detail in Chaps. 6 and 7. Figure 1.3, left, represents a simple Feynman diagram, in which an electron and a proton are mutually scattered as the result of an electromagnetic interaction (virtual photon exchange) between them. This process requires two vertices in which the photon interacts with the charged particle (one for each particle), and for this kind of scattering this is the minimum number of vertices—we say that this is the representation of the process at *leading order*.

The Feynman rules allow associating to each vertex a multiplication factor contributing to the total “amplitude”; the probability of a process is proportional to the square of the amplitude. For example in the case of a photon coupling (two photon vertices) this factor is the “coupling parameter”

$$\frac{1}{4\pi\epsilon_0} \frac{e^2}{\hbar c} \simeq \frac{1}{137}$$

for each photon, so the amplitudes for diagrams with many photons (see for example Fig. 1.3, right) are small, compared to those with only one.

Technically, the Feynman rules allow expressing the probability of a process as a power series expansion in the coupling parameter. One can draw all possible diagrams up to some number of mediators of the exchange, depending on the accuracy desired; then compute the amplitude for each diagram following the Feynman rules, sum all the amplitudes (note that the diagrams could display negative interference), and calculate the square of the modulus of the amplitude, which will give the probability. This perturbative technique is only of practical use when the coupling parameter is small, that is, as we shall see, for electromagnetic or weak interactions, but not for strong interactions, except at very high energies (the coupling parameter of strong interactions decreases with energy).

1.5 A Quick Look at the Universe

The origin and destiny of the Universe are, for most researchers, the fundamental question. Many answers were provided over the ages, a few of them built over scientific observations and reasoning. Over the last century enormous scientific theoretical and experimental breakthroughs have occurred: less than a century ago, people

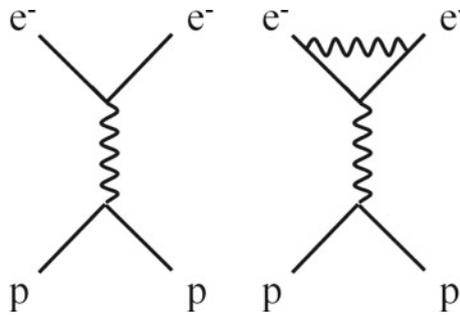


Fig. 1.3 Electromagnetic scattering: interaction between an electron and a proton. Left: via the exchange of one virtual photon. Right: the same process with one more virtual photon—the amplitude decreases by a factor of approximately $1/137$

believed that the Milky Way, our own galaxy, was the only galaxy in the Universe; now we know that there are 10^{11} galaxies within the observable universe, each containing some 10^{11} stars. Most of them are so far away that we cannot even hope to explore them.

Let us start an imaginary trip across the Universe from the Earth. The Earth, which has a radius of about 6400 km, is one of the planets orbiting around the Sun (we shall often identify the Sun with the symbol \odot , which comes from its hieroglyphic representation). The latter is a star with a mass of about 2×10^{30} kg located at a distance from us of about 150 million km (i.e., 500 light seconds). We call the average Earth–Sun distance the astronomical unit, in short AU or au. The ensemble of planets orbiting the Sun is called the solar system. Looking to the aphelion of the orbit of the farthest acknowledged planet, Neptune, the solar system has a diameter of 9 billion km (about 10 light hours, or 60 AU).

The Milky Way (Fig. 1.4) is the galaxy that contains our solar system. Its name “milky” is derived from its appearance as a dim glowing band arching across the night sky in which the naked eye cannot distinguish individual stars. The ancient Romans named it “via lactea,” which literally corresponds to the present name (being *lac* the latin word for milk)—the term “galaxy,” too, descends from a Greek word indicating milk. Seen from Earth with the unaided eye, the Milky Way appears as a band because its disk-shaped structure is viewed edge-on from the periphery of the galaxy itself. Galilei⁹ first resolved such band of light into individual stars with his telescope, in 1610.

⁹Galileo Galilei (1564–1642) was an Italian physicist, mathematician, astronomer, and philosopher who deeply influenced the scientific thought down to the present days. He first formulated some of the fundamental laws of mechanics, like the principle of inertia and the law of accelerated motion; he formally proposed, with some influence from previous works by Giordano Bruno, the principle of relativity. Galilei was professor in Padua, nominated by the Republic of Venezia, and astronomer in Firenze. He built the first practical telescope (using lenses) and using this instrument he could perform astronomical observations which supported Copernicanism; in particular he discovered the phases of Venus, the four largest satellites of Jupiter (named the Galilean moons in his honor), and he observed and analyzed sunspots. Galilei also made major discoveries in military science

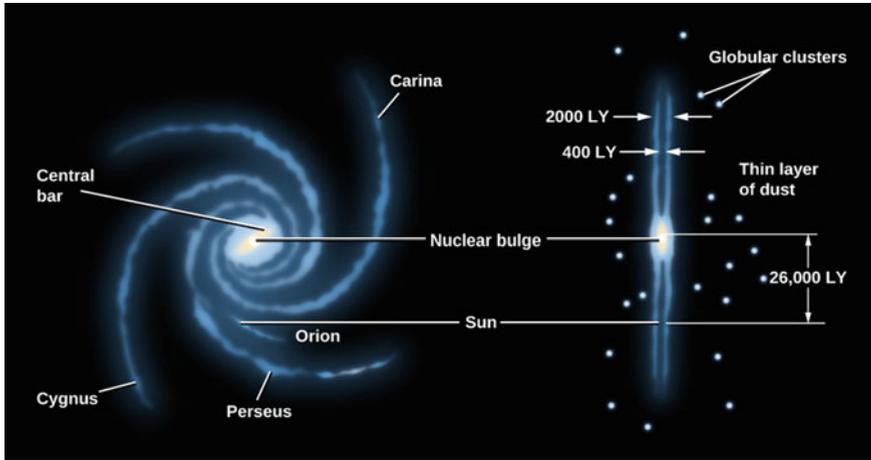


Fig. 1.4 The Milky Way seen from top and from side. From <https://courses.lumenlearning.com/astronomy>

The Milky Way is a spiral galaxy some 100 000 light-years (ly) across, 1000 ly to 2000 ly thick, with the solar system located within the disk, about 30 000 ly away from the galactic center in the so-called Orion arm. The stars in the inner 10 000 ly form a bulge and a few bars that radiate from the bulge. The very center of the galaxy, in the constellation of Sagittarius, hosts a supermassive black hole of some 4 million solar masses, as determined by studying the orbits of nearby stars. The interstellar medium (ISM) is filled by partly ionized gas, dust, and cosmic rays, and it accounts for some 15% of the total mass of the disk. The gas is inhomogeneously distributed and it is mostly confined to discrete clouds occupying a few percent of the volume. A magnetic field of a few μG interacts with the ISM.

With its $\sim 10^{11}$ stars, the Milky Way is a relatively large galaxy. Teaming up with a similar-sized partner (called the Andromeda galaxy), it has gravitationally trapped many smaller galaxies: together, they all constitute the so-called Local Group. The Local Group comprises more than 50 galaxies, including numerous dwarf galaxies—some are just spherical collections of hundreds of stars that are called globular clusters. Its gravitational center is located somewhere between the Milky Way and the Andromeda galaxies. The Local Group covers a diameter of 10 million light-years, or 10 Mly (i.e., 3.1 megaparsec,¹⁰ Mpc); it has a total mass of about 10^{12} solar masses.

and technology. He came into conflict with the Catholic Church, for his support of Copernican theories. In 1616 the Inquisition declared heliocentrism to be heretical, and Galilei was ordered to refrain from teaching heliocentric ideas. Galilei argued that tides were an additional evidence for the motion of the Earth. In 1633 the Roman Inquisition found Galilei suspect of heresy, sentencing him to indefinite imprisonment; he was kept under house arrest in Arcetri, near Florence, until his death.

¹⁰The parsec (symbol: pc, and meaning “parallax of one arcsecond”) is often used in astronomy to measure distances to objects outside the solar system. It is defined as the length of the longer leg of

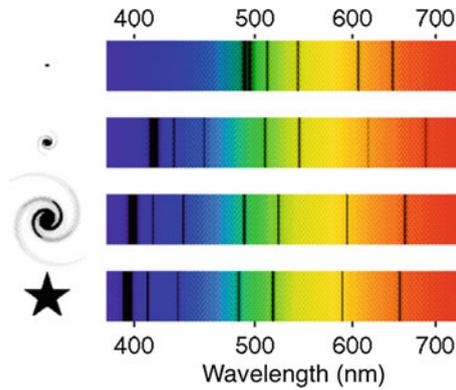


Fig. 1.5 Redshift of emission spectrum of stars and galaxies at different distances. A star in our galaxy is shown at the bottom left with its spectrum on the bottom right. The spectrum shows the dark absorption lines, which can be used to identify the chemical elements involved. The other three spectra and pictures from bottom to top show a nearby galaxy, a medium distance galaxy, and a distant galaxy. Using the redshift we can calculate the relative radial velocity between these objects and the Earth. From <http://www.indiana.edu>

Galaxies are not uniformly distributed; most of them are arranged into groups (containing some dozens of galaxies) and clusters (up to several thousand galaxies); groups and clusters and additional isolated galaxies form even larger structures called superclusters that may span up to 100 Mly.

This is how far our observations can go.

In 1929 the American astronomer Edwin Hubble, studying the emission of radiation from galaxies, compared their speed (calculated from the Doppler shift of their emission lines) with the distance (Fig. 1.5), and discovered that objects in the Universe move away from us with velocity

$$v = H_0 d, \tag{1.1}$$

where d is the distance to the object, and H_0 is a parameter called the Hubble constant (whose value is known today to be about $68 \text{ km s}^{-1} \text{ Mpc}^{-1}$, i.e., $21 \text{ km s}^{-1} \text{ Mly}^{-1}$). The above relation is called Hubble’s law (Fig. 1.6). Note that at that time galaxies beyond the Milky Way had just been discovered.

The Hubble law means that sources at cosmological distances (where local motions, often resulting from galaxies being in gravitationally bound states, are negligible) are observed to move away at speeds that are proportionally higher for larger distances. The Hubble constant describes the rate of increase of recession velocities for increasing distance. The Doppler redshift

a right triangle, whose shorter leg corresponds to one astronomical unit, and the subtended angle of the vertex opposite to that leg is one arcsecond. It corresponds to approximately 3×10^{16} m, or about 3.26 light-years. Proxima Centauri, the nearest star, is about 1.3 pc from the Sun.

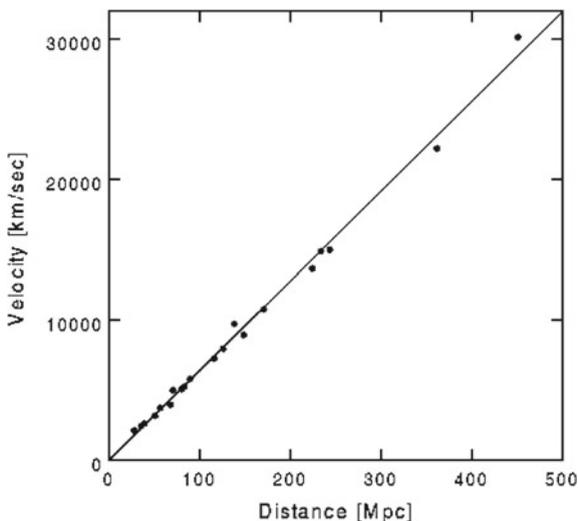


Fig. 1.6 Experimental plot of the relative velocity (in km/s) of known astrophysical objects as a function of distance from Earth (in Mpc). Several methods are used to determine the distances. Distances up to hundreds of parsecs are measured using stellar parallax (i.e., the difference between the angular positions from the Earth with a time difference of 6 months). Distances up to 50 Mpc are measured using Cepheids, i.e., periodically pulsating stars for which the luminosity is related to the pulsation period (the distance can thus be inferred by comparing the intrinsic luminosity with the apparent luminosity). Finally, distances from 1 to 1000 Mpc can be measured with another type of standard candle, Type Ia supernova, a class of remnants of imploded stars. From 15 to 200 Mpc, the Tully–Fisher relation, an empirical relationship between the intrinsic luminosity of a spiral galaxy and the width of its emission lines (a measure of its rotation velocity), can be used. The methods, having large superposition regions, can be cross-calibrated. The line is a Hubble law fit to the data. From A. G. Riess, W. H. Press and R. P. Kirshner, *Astrophys. J.* 473 (1996) 88

$$z = \frac{\lambda'}{\lambda} - 1$$

can thus also be used as a metric of the distance of objects. To give an idea of what H_0 means, the speed of revolution of the Earth around the Sun is about 30 km/s. Andromeda, the large galaxy closest to the Milky Way, is at a distance of about 2.5 Mly from us—however we and Andromeda are indeed approaching; this is an example of the effect of local motions.

Dimensionally, we note that H_0 is the inverse of a time: $H_0 \simeq (14 \times 10^9 \text{ years})^{-1}$. A simple interpretation of the Hubble law is that, if the Universe had always been expanding at a constant rate, about 14 billion years ago its volume was zero—naively, we can think that it exploded through a quantum singularity, such an explosion being usually called the “Big Bang.” This age is consistent with present estimates of the age of the Universe within gravitational theories, which we shall discuss later in this book, and slightly larger than the age of the oldest stars, which can be measured from the presence of heavy nuclei. The picture looks consistent.

The adiabatic expansion of the Universe entails a freezing with expansion, which in the nowadays quiet Universe can be summarized as a law for the evolution of the temperature T with the size R ,

$$T \propto \frac{1}{R(t)}.$$

The present temperature is slightly less than 3 K and can be measured from the spectrum of the blackbody (microwave) radiation (the so-called cosmic microwave background, or CMB, permeating the Universe). The formula implies also that studying the ancient Universe in some sense means exploring the high-energy world: subatomic physics and astrophysics are naturally connected.

Tiny quantum fluctuations in the distribution of cosmic energy at epochs corresponding to fractions of a second after the Big Bang led to galaxy formation. Density fluctuations grew with time into proto-structures which, after accreting enough mass from their surroundings, overcame the pull of the expanding universe and after the end of an initial era dominated by radiation collapsed into bound, stable structures. The average density of such structures was reminiscent of the average density of the Universe when they broke away from the Hubble expansion: so, earlier-forming structures have a higher mean density than later-forming structures. Proto-galaxies were initially dark. Only later, when enough gas had fallen into their potential well, stars started to form—again, by gravitational instability in the gas—and shine due to the nuclear fusion processes activated by the high temperatures caused by gravitational forces. The big picture of the process of galaxy formation is probably understood by now, but the details are not. The morphological difference between disk (i.e., spiral) galaxies and spheroidal (i.e., elliptical) galaxies are interpreted as due to the competition between the characteristic timescale of the infall of gas into the protogalaxy's gravitational well and the timescale of star formation: if the latter is shorter than the former, a spheroidal (i.e., three-dimensional) galaxy likely forms; if it is longer, a disk (i.e., two-dimensional) galaxy forms. A disk galaxy is rotation supported, whereas a spheroidal galaxy is pressure supported—stars behaving in this case like gas molecules. It is conjectured that the velocity dispersion (~ 200 km/s) among proto-galaxies in the early Universe may have triggered rotation motions in disk galaxies, randomly among galaxies but orderly within individual galaxies.

Stars also formed by gravitational instabilities of the gas. For given conditions of density and temperature, gas (mostly hydrogen and helium) clouds collapse and, if their mass is suitable, eventually form stars. Stellar masses are limited by the conditions that (i) nuclear reactions can switch on in the stellar core (>0.1 solar masses), and (ii) the radiation drag of the produced luminosity on the plasma does not disrupt the star's structure (<100 solar masses). For a star of the mass of the Sun, formation takes 50 million years—the total lifetime is about 11 billion years before collapsing to a “white dwarf,” and in the case of our Sun some 4.5 billion years are already gone.

Stars span a wide range of luminosities and colors and can be classified according to these characteristics. The smallest stars, known as red dwarfs, may contain as little as 10% the mass of the Sun and emit only 0.01% as much energy, having typical

surface temperatures of 3000 K, i.e., roughly half the surface temperature of the Sun. Red dwarfs are by far the most numerous stars in the Universe and have lifetimes of tens of billions of years, much larger than the age of the Universe. On the other hand, the most massive stars, known as hypergiants, may be 100 or more times more massive than the Sun, and have surface temperatures of more than 40 000 K. Hypergiants emit hundreds of thousands of times more energy than the Sun, but have lifetimes of only a few million years. They are thus extremely rare today and the Milky Way contains only a handful of them.

Luminosity,¹¹ radius and temperature of a star are in general linked. In a temperature-luminosity plane, most stars populate a locus that can be described (in log scale) as a straight line (Fig. 1.7): this is called the *main sequence*. Our Sun is also found there—corresponding to very average temperature and luminosity.

The fate of a star depends on its mass. The heavier the star, the larger its gravitational energy, and the more effective are the nuclear processes powering it. In average stars like the Sun, the outer layers are supported against gravity until the stellar core stops producing fusion energy; then the star collapses as a “white dwarf”—an Earth-sized object. Main-sequence stars over 8 solar masses can die in a very energetic explosion called a (core-collapse, or Type II) supernova. In a supernova, the star’s core, made of iron (which being the most stable atom, i.e., one whose mass defect per nucleon is maximum, is the endpoint of nuclear fusion processes, Fig. 1.8) collapses and the released gravitational energy goes on heating the overlying mass layers which, in an attempt to dissipate the sudden excess heat by increasing the star’s radiating surface, expand at high speed (10 000 km/s and more) to the point that the star gets quickly disrupted—i.e., explodes. Supernovae release an enormous amount of energy, about 10^{46} J—mostly in neutrinos from the nuclear processes occurring in the core, and just 1% in kinetic energies of the ejecta—in a few tens of seconds.¹² For a period of days to weeks, a supernova may outshine its entire host galaxy. Being the

¹¹The brightness of a star at an effective wavelength λ as seen by an observer on Earth is given by its apparent *magnitude*. This scale originates in the Hellenistic practice of dividing stars into six magnitudes: the brightest stars were said to be of first magnitude ($m = 1$), while the faintest were of sixth magnitude ($m = 6$), the limit of naked eye human visibility. The system is today formalized by defining a first magnitude star as a star that is 100 times as bright as a sixth magnitude star; thus, a first magnitude star is $\sqrt[3]{100}$ (about 2.512) times as bright as a second magnitude star (obviously the brighter an object appears, the lower the value of its magnitude). The stars Arcturus and Vega have an apparent magnitude approximately equal to 0. The absolute magnitude M_V is defined to be the visual ($\lambda \sim 550$ nm) apparent magnitude that the object would have if it were viewed from a distance of 10 parsec, in the absence of light extinction; it is thus a measure of the luminosity of an object. The problem of the relation between apparent magnitude, absolute magnitude, and distance is related also to cosmology, as discussed in Chap. 8. The absolute magnitude is nontrivially related to the bolometric luminosity, i.e., to the total electromagnetic power emitted by a source; the relation is complicated by the fact that only part of the emission spectrum is observed in a photometric band. The absolute magnitude of the Sun is $M_{V, \odot} \simeq 4.86$, and its absolute bolometric magnitude is $M_{\text{bol}, \odot} \simeq 4.76$; the difference $M_V - M_{\text{bol}}$ (for the Sun, $M_{V, \odot} - M_{\text{bol}, \odot} \simeq 0.1$) is called the bolometric correction BC, which is a function of the temperature. It can be approximated as $BC(T) \simeq 29500/T + 10 \log_{10} T - 42.62$.

¹²Note that frequently astrophysicist use as a unit of energy the old “cgs” (centimeter–gram–second) unit called *erg*; $1 \text{ erg} = 10^{-7} \text{ J}$.

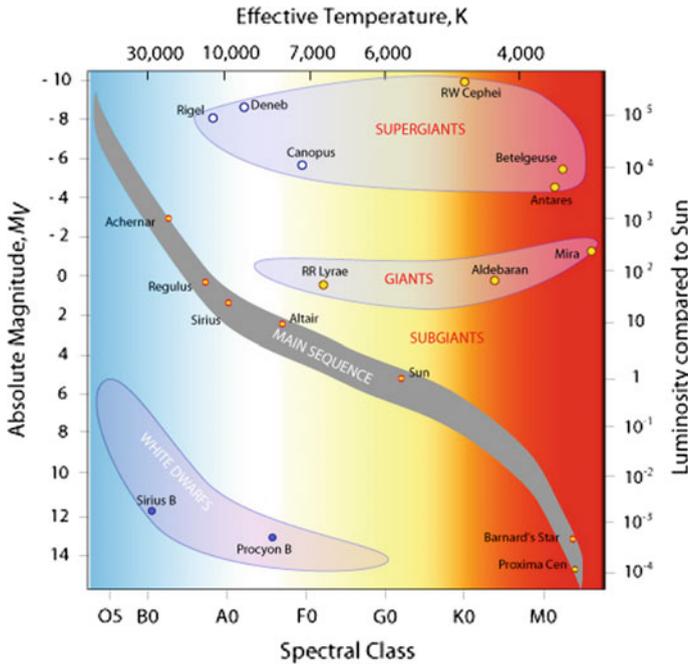


Fig. 1.7 Hertzsprung–Russell diagram plotting the luminosities of stars versus their stellar classification or effective temperature (color). From <http://www.atnf.csiro.au/outreach/education>

energy of the explosion large enough to generate hadronic interactions, basically any element and many subatomic particles are produced in these explosions. On average, in a typical galaxy (e.g., the Milky Way) supernova explosions occur just once or twice per century. Supernovae leave behind neutron stars or black holes.¹³

The heavier the star, the more effective the fusion process, and the shorter the lifetime. We need a star like our Sun, having a lifetime of a few tens of billion of years, to both give enough time to life to develop and to guarantee high enough temperatures for humans. The solar system is estimated to be some 4.6 billion years old and to have started from a molecular cloud. Most of the collapsing mass collected in the center, forming the Sun, while the rest flattened into a disk out of which the planets formed. The Sun is too young to have created heavy elements in such an abundance to justify carbon-based life on Earth. The carbon, nitrogen, and oxygen atoms in our bodies, as well as atoms of all other heavy elements, were created in previous generations of stars somewhere in the Universe.

¹³The Chandrasekhar limit is the maximum mass theoretically possible for a star to end its lifecycle into a dwarf star: Chandrasekhar in 1930 demonstrated that it is impossible for a collapsed star to be stable if its mass is greater than ~ 1.44 times the mass of the Sun. Above 1.5–3 solar masses (the limit is not known, depending on the initial conditions) a star ends its nuclear-burning lifetime into a black hole. In the intermediate range it will become a neutron star.

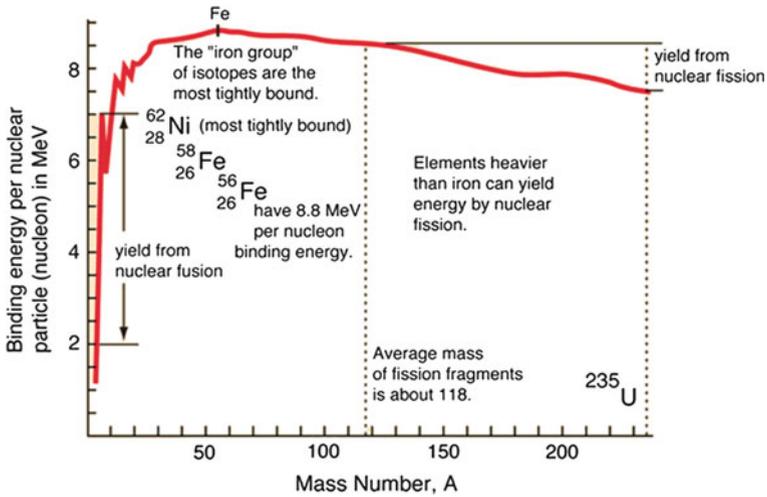
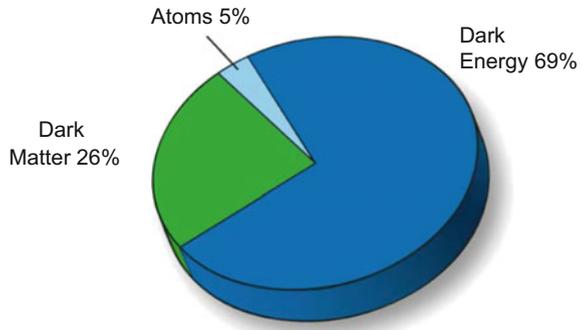


Fig. 1.8 Binding energy per nucleon for stable atoms. Iron (^{56}Fe) is the stable element for which the binding energy per nucleon is the largest (about 8.8 MeV); it is thus the natural endpoint of processes of fusion of lighter elements, and of fission of heavier elements (although ^{58}Fe and ^{62}Ni have a slightly higher binding energy, by less than 0.05%, they are subject to nuclear photodisintegration). From <http://hyperphysics.phy-astr.gsu.edu>

Fig. 1.9 Present energy budget of the Universe



The study of stellar motions in galaxies indicates the presence of a large amount of unseen mass in the Universe. This mass seems to be of a kind presently unknown to us; it neither emits nor absorbs electromagnetic radiation (including visible light) at any significant level. We call it *dark matter*: its abundance in the Universe amounts to an order of magnitude more than the conventional matter we are made of. Dark matter represents one of the greatest current mysteries of astroparticle physics. Indications exist also of a further form of energy, which we call *dark energy*. Dark energy contributes to the total energy budget of the Universe three times more than dark matter.

The fate of the Universe depends on its energy content. In the crude approximation of a homogeneous and isotropic Universe with a flat geometry, the escape velocity v_{esc} of an astrophysical object of mass m at a distance r from a given point can be computed from the relation

$$\frac{mv_{\text{esc}}^2}{2} - GM\frac{m}{r} = \frac{mv_{\text{esc}}^2}{2} - G \left[\left(\frac{4}{3}\pi r^3 \right) \frac{\rho}{c^2} \right] \frac{m}{r} = 0 \implies v_{\text{esc}} = \sqrt{\frac{8}{3}\pi G r^2 \frac{\rho}{c^2}},$$

where $M = \left(\frac{4}{3}\pi r^3\right) \rho/c^2$ is the amount of mass in the sphere of radius r , ρ being the average energy density, and G the gravitational constant. Given Hubble's law, if

$$v = H_0 r < v_{\text{esc}} = \sqrt{\frac{8}{3}\pi G r^2 \frac{\rho}{c^2}} \implies \rho > \rho_{\text{crit}} = \frac{3H_0^2 c^2}{8\pi G}$$

the Universe will eventually recollapse, otherwise it will expand forever. ρ_{crit} , about $5 \text{ GeV}/\text{m}^3$, is called the critical energy density of the Universe.

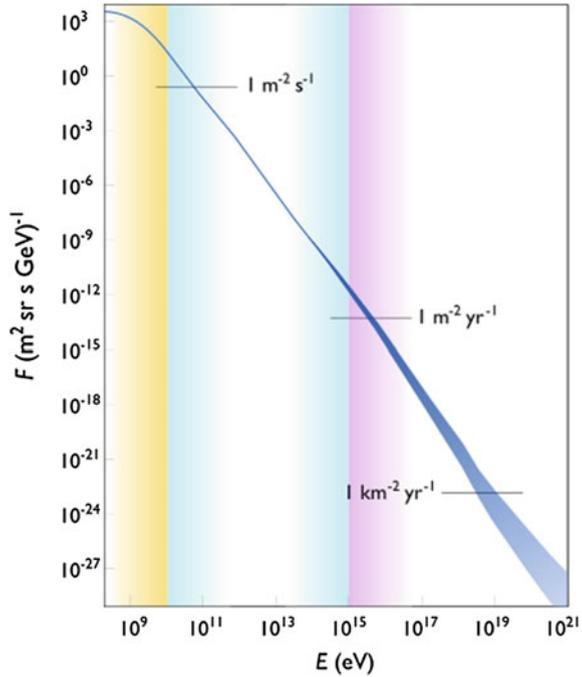
In summary, we live in a world that is mostly unknown even from the point of view of the nature of its main constituents (Fig. 1.9). The evolution of the Universe and our everyday life depend on this unknown external world. First of all, the ultimate destiny of the Universe—a perpetual expansion or a recollapse—depends on the amount of all the matter in the Universe. Moreover, every second, high-energy particles (i.e., above 1 GeV) of extraterrestrial origin pass through each square centimeter on the Earth, and they are messengers from regions where highly energetic phenomena take place that we cannot directly explore. These are the so-called *cosmic rays*, discovered in the beginning of the nineteenth century (see Chap. 3). It is natural to try to use these messengers in order to obtain information on the highest energy events occurring in the Universe.

1.6 Cosmic Rays

The distribution in energy (the so-called energy spectrum) of cosmic rays¹⁴ is quite well described by a power law E^{-p} with p a positive number (Fig. 1.10). The spectral index p is around 3 on average. After the low-energy region dominated by cosmic rays from the Sun (the solar wind), the spectrum becomes steeper for energy values of less than $\sim 1000 \text{ TeV}$ (150 times the maximum energy foreseen for the beams of the LHC collider at CERN): this is the energy region that we know to be dominated by cosmic rays produced by astrophysical sources in our Galaxy, the Milky Way. For higher energies a further steepening occurs, the point at which this change of slope takes place being called the “knee.” Some believe that the region above

¹⁴In this textbook we define as *cosmic rays* all particles of extraterrestrial origin. It should be noted that other textbooks instead define as cosmic rays only nuclei, or only protons and ions—i.e., they separate gamma rays and neutrinos from cosmic rays.

Fig. 1.10 Energy spectrum (number of incident particles per unit of energy, per second, per unit area, and per unit of solid angle) of the primary cosmic rays. The vertical band on the left indicates the energy region in which the emission from the Sun is supposed to be dominant; the central band the region in which most of the emission is presumably of galactic origin; the band on the right the region of extragalactic origin. By Sven Lafebre (own work) [GFDL <http://www.gnu.org/copyleft/fdl.html>], via Wikimedia Commons



this energy is dominated by cosmic rays produced by extragalactic sources, mostly supermassive black holes growing at the centers of other galaxies. For even higher energies (more than one million TeV) the cosmic-ray spectrum becomes less steep, resulting in another change of slope, called the “ankle”; some others believe that the knee is caused by a propagation effect, and the threshold for the dominance of extragalactic sources is indeed close to the ankle. Finally, at the highest energies in the figure a drastic suppression is present—as expected from the interaction of long-traveling particles with the cosmic microwave background, remnant of the origin of the Universe.¹⁵

The majority of high-energy particles in cosmic rays are protons (hydrogen nuclei); about 10% are helium nuclei (nuclear physicists usually call them alpha particles), and 1% are neutrons or nuclei of heavier elements. Together, these account

¹⁵A theoretical upper limit on the energy of cosmic rays from distant sources was computed in 1966 by Greisen, Kuzmin, and Zatsepin, and it is called today the GZK cutoff. Protons with energies above a threshold of about 10^{20} eV suffer a resonant interaction with the cosmic microwave background photons to produce pions through the formation of a short-lived particle (resonance) called Δ : $p + \gamma \rightarrow \Delta \rightarrow N + \pi$. This continues until their energy falls below the production threshold. Because of the mean path associated with the interaction, extragalactic cosmic rays from distances larger than 50 Mpc from the Earth and with energies greater than this threshold energy should be strongly suppressed on Earth, and there are no known sources within this distance that could produce them. A similar effect (nuclear photodisintegration) limits the mean free path for the propagation of nuclei heavier than the proton.

for 99% of cosmic rays, and electrons and photons make up the remaining 1%. Note that the composition is expected to vary with energy; given the energy dependence of the flux, however, only the energies below the knee are responsible for this proportion. The number of neutrinos is estimated to be comparable to that of high-energy photons, but it is very high at low energies because of the nuclear processes that occur in the Sun: such processes involve a large production of neutrinos.

Neutral and stable cosmic messengers (gamma rays, high-energy neutrinos, gravitational waves) are very precious since they are not deflected by extragalactic (order of 1 nG–1 fG) or by galactic (order of 1 μ G) magnetic fields and allow pointing directly to the source. While we detect a large flux of gamma rays and we know several cosmic production sites, evidence for astrophysical neutrinos and gravitational waves was only recently published, respectively in 2014 and in 2016.

Cosmic rays hitting the atmosphere (called primary cosmic rays) generally produce secondary particles that can reach the Earth's surface, through multiplicative showers.

About once per minute, a single subatomic particle enters the Earth's atmosphere with an energy larger than 10 J. Somewhere in the Universe there are accelerators that can impart to single protons energies 100 million times larger than the energy reached by the most powerful accelerators on Earth. It is thought that the ultimate engine of the acceleration of cosmic rays is gravity. In gigantic gravitational collapses, such as those occurring in supernovae (stars imploding at the end of their lives, see Fig. 1.11, left) and in the accretion of supermassive black holes (equivalent to millions to billions of solar masses) at the expense of the surrounding matter (Fig. 1.11, right), part of the potential gravitational energy is transformed, through not fully understood mechanisms, into kinetic energy of the particles.

The reason why the maximum energy attained by human-made accelerators with the presently known acceleration technologies cannot compete with the still mysterious cosmic accelerators is simple. The most efficient way to accelerate particles requires their confinement within a radius R by a magnetic field B , and the final energy is proportional to the product $R \times B$. On Earth, it is difficult to imagine reasonable confinement radii greater than one hundred kilometers, and magnetic fields stronger than 10 T (i.e., one hundred thousand times the Earth's magnetic field). This combination can provide energies of a few tens of TeV, such as those of the LHC accelerator at CERN. In nature, accelerators with much larger radii exist, such as supernova remnants (light-years) and active galactic nuclei (tens of thousands of light-years). Of course human-made accelerators have important advantages, such as being able to control the flux and the possibility of knowing the initial conditions (cosmic ray researchers do not know a-priori the initial conditions of the phenomena they study).

Among cosmic rays, photons are particularly important. As mentioned above, the gamma photons (called gamma rays for historical reasons) are photons of very high energy and occupy the most energetic part of the electromagnetic spectrum; being neutral they can travel long distances without being deflected by galactic and extragalactic magnetic fields; hence, they allow us to directly study their emission sources. These facts are now pushing us to study in particular the high-energy gamma



Fig. 1.11 Left: The remnant of the supernova in the Crab region (Crab nebula), a powerful gamma emitter in our Galaxy. The supernova exploded in 1054 and the phenomenon was recorded by Chinese astronomers. Until 2010, most astronomers regarded the Crab as a standard candle for high-energy photon emission, but recently it was discovered that the Crab Nebula from time to time flickers. Anyway, most plots of sensitivity of detectors refer to a “standard Crab” as a reference unit. The vortex around the center is visible; a neutron star rapidly rotating (with a period of around 30 ms) and emitting pulsed gamma-ray streams (pulsar) powers the system. Some supernova remnants, seen from Earth, have an apparent dimension of a few tenths of a degree—about the dimension of the Moon. Right: A supermassive black hole accretes, swallowing neighboring stellar bodies and molecular clouds, and emits jets of charged particles and gamma rays. Credits: NASA

rays and cosmic rays of hundreds of millions of TeV. However, gamma rays are less numerous than charged cosmic rays of the same energy, and the energy spectrum of charged cosmic rays is such that particles of hundreds of millions of TeV are very rare. The task of experimental physics is, as usual, challenging, and often discoveries correspond to breakthroughs in detector techniques.

A sky map of the emitters of very high-energy photons in galactic coordinates¹⁶ is shown in Fig. 1.12. One can identify both galactic emitters (in the equatorial plane)

¹⁶Usually the planar representations of maps of the Universe are done in galactic coordinates. To understand what this means, let us start from a celestial coordinate system in spherical coordinates, in which the Sun is at the center, the primary direction is the one joining the Sun with the center of the Milky Way, and the galactic plane is the fundamental plane. Coordinates are positive toward North and East in the fundamental plane.

We define as galactic longitude (l or λ) the angle between the projection of the object in the galactic plane and the primary direction. Latitude (symbol b or ϕ) is the angular distance between the object and the galactic plane. For example, the North galactic pole has a latitude of $+90^\circ$.

Plots in galactic coordinates are then projected onto a plane, typically using an elliptical (Mollweide or Hammer; we shall describe the Mollweide projection here) projection preserving areas. The Mollweide projection transforms latitude and longitude to plane coordinates x and y via the equations (angles are expressed in radians):

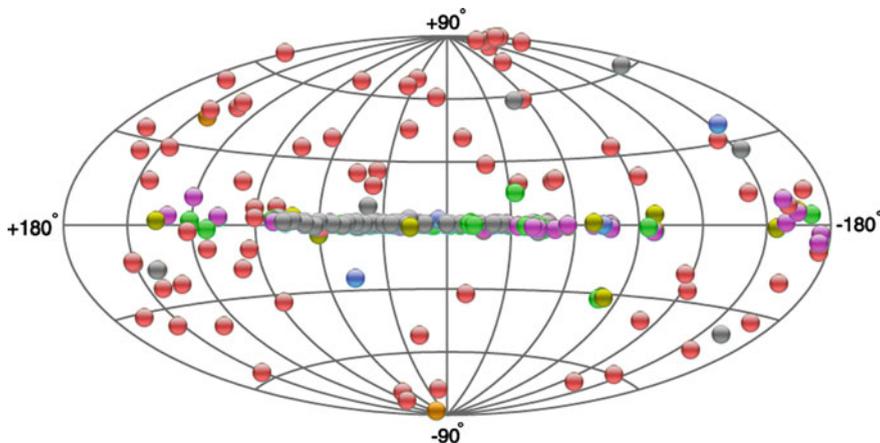


Fig. 1.12 Map of the emitters of photons above 100 GeV in the Universe, in galactic coordinates (from the TeVCAT catalog). The sources are indicated as circles—the colors represent different kinds of emitters which will be explained in Chap. 10. From <http://tevcat.uchicago.edu/> (February 2018)

and extragalactic emitters. The vast majority of the galactic emitters is associated to remnants of supernovae, while extragalactic emitters are positionally consistent with active galaxies—instruments do not have the resolution needed to study the morphology of galaxies outside the local group.

1.7 Multimessenger Astrophysics

Physicists and astronomers have studied during millennia the visible light coming from astrophysical objects. The twentieth century has been the century of multiwave-

$$\begin{aligned}
 x &= R \frac{2\sqrt{2}}{\pi} \cos \theta \\
 y &= R\sqrt{2} \sin \theta ,
 \end{aligned}$$

where θ is defined by the equation

$$2\theta + \sin(2\theta) = \pi \sin \phi$$

and R is the radius of the sphere to be projected. The map has area $4\pi R^2$, obviously equal to the surface area of the generating globe. The x -coordinate has a range $[-2R\sqrt{2}, 2R\sqrt{2}]$, and the y -coordinate has a range $[-R\sqrt{2}, R\sqrt{2}]$. The galactic center is located at $(0, 0)$.

Less frequently, a projection using equatorial coordinates is used. In this case, the origin is at the center of Earth; the fundamental plane is the projection of Earth’s equator onto the celestial sphere, and the primary direction is toward the March equinox; the projection of the galactic plane is a curve in the ellipse.

length astronomy: information from light at different wavelengths (radio, microwave, infrared, UV, X-ray, and gamma ray) became available and is allowing us, in a joint effort with optical astronomy, to learn more about the various physical processes that occur throughout the Universe.

In the last decade, the detections of astrophysical neutrinos, and especially the detection of gravitational waves, allowed us to learn about objects that were invisible to other astronomical methods, for example merging black hole systems. The new observations paved the way for a new field of research called multimessenger astrophysics: combining the information obtained from the detection of photons, neutrinos, charged particles, and gravitational waves can shed light on completely new phenomena and objects.

Further Reading

- [F1.1] A. Einstein and L. Infeld, “The Evolution of Physics,” Touchstone. This inspiring book is about the main ideas in physics. With simplicity and a limited amount of formulas it gives an exciting account for the advancement of science down to the early quantum theory.
- [F1.2] L. Lederman and D. Teresi, “The God Particle: If the Universe Is the Answer, What Is the Question?,” Dell. This book provides a history of particle physics starting from Greek philosophers down to modern quantum physics.
- [F1.3] G. Smoot and K. Davidson, “Wrinkles in Time,” Harper. This book discusses modern cosmology in a simple way.
- [F1.4] S. Weinberg, “To Explain the World,” Harper. This book discusses the evolution of modern science.

Exercises

1. *Size of a molecule.* Explain how you will be able to find the order of magnitude of the size of a molecule using a drop of oil. Make the experiment and check the result.
2. *Thomson atom.* Consider the Thomson model of the atom applied to a helium atom (the two electrons are in equilibrium inside a homogeneous positive-charged sphere of radius $r \sim 10^{-10}$ m).
 - (a) Determine the distance of the electrons to the center of the sphere.
 - (b) Determine the vibration frequency of the electrons in this model and compare it to the first line of the spectrum of hydrogen, at $E \simeq 10.2$ eV.
3. *Atom as a box.* Consider a simplified model where the hydrogen atom is described by a one-dimensional box of length r with the proton at its center and where the electron is free to move around. Compute, considering the Heisenberg uncertainty principle, the total energy of the electron as a function of r and determine the value of r for which this energy is minimized.
4. *Naming conventions for particles.* Write down the symbol, charge, and approximate mass for the following particles:
 - (a) tau lepton;

- (b) antimuon-neutrino;
 - (c) charm quark;
 - (d) anti-electron;
 - (e) antibottom quark.
5. *Strange mesons.* How many quark combinations can you make to build a strange neutral meson, using u , d , and s quarks?
 6. *The Universe.* Find a dark place close to where you live, and go there in the night. Try to locate the Milky Way and the galactic center. Comment on your success (or failure).
 7. *Telescopes.* Research the differences between Newtonian and Galileian telescopes; discuss such differences.
 8. *Number of stars in the Milky Way.* Our Galaxy consists of a disk of a radius $r_d \simeq 15$ kpc about $h_d \simeq 300$ pc thick, and a spherical bulge at its center roughly 3 kpc in diameter. The distance between our Sun and our nearest neighboring stars, the Alpha Centauri system, is about 1.3 pc. Estimate the number of stars in our galaxy.
 9. *Number of nucleons in the Universe.* Estimate the number of nucleons in the Universe.
 10. *Hubble's law.* The velocity of a galaxy can be measured using the Doppler effect. The radiation coming from a moving object is shifted in wavelength, the relation being, for $\Delta\lambda/\lambda \ll 1$,

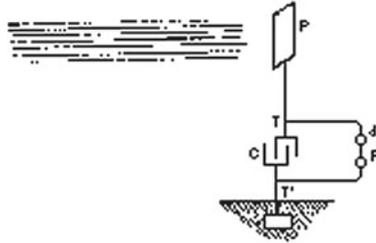
$$z = \frac{\Delta\lambda}{\lambda} \simeq \frac{v}{c},$$

where λ is the rest wavelength of the radiation, $\Delta\lambda$ is the observed wavelength minus the rest wavelength, and v is defined as positive when the object parts away from the observer. Notice that (for v small compared to the speed of light) the formula is the same as for the classical Doppler effect.

An absorption line that is found at 500 nm in the laboratory is measured at 505 nm when analyzing the spectrum of a particular galaxy. Estimate the distance of the galaxy.

11. *Luminosity and magnitude.* Suppose that you burn a car on the Moon, heating it at a temperature of 3000 K. What is the absolute magnitude of the car? What is the apparent magnitude m seen at Earth?
12. *Cosmic ray fluxes and wavelength.* The most energetic particles ever observed at Earth are cosmic rays. Make an estimation of the number of such events with an energy between 3×10^{18} and 10^{19} eV that may be detected in one year by an experiment with a footprint of 1000 km^2 . Evaluate the structure scale that can be probed by such particles.
13. *Energy from cosmic rays: Nikola Tesla's "free" energy generator.* "This new power for the driving of the world's machinery will be derived from the energy which operates the universe, the cosmic energy, whose central source for the Earth is the Sun and which is everywhere present in unlimited quantities." Immediately after the discovery of natural radioactivity, in 1901, Nikola Tesla patented

an engine using the energy involved (and expressed a conjecture about the origin of such radioactivity). Below, we show a drawing (made by Tesla himself) of Tesla's first radiant energy receiver. If an antenna (the higher the better: why?) is wired to one side of a capacitor (the other going to ground), the potential difference will charge the capacitor. Suppose you can intercept all high-energy cosmic radiation (assume 1 particle per square centimeter per second with an average energy of 3 GeV); what is the power you could collect with a 1 m² antenna, and how does it compare with solar energy?



- 14. *Galactic and extragalactic emitters of gamma rays.* In Fig. 1.12, more than half of the emitters of high-energy photons lie in the galactic plane (the equatorial line). Guess why.