Cambridge University Press
978-0-521-79480-0 - Our Cosmic Origins: From the Big Bang to the Emergence of Life and Intelligence
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LOCATING HUMANS IN THE UNIVERSE

'For what is Man in nature? A nothingness in respect to infinity, a whole in respect to nothingness, a median between nothing and everything'

Blaise Pascal, *Les Pensées*, 1670

Introduction

Even more than the Renaissance period, the twentieth century will be remembered in human memory as an extraordinary era in every regard. The awareness of our true position, and of our isolation, in an immense and mysterious Universe began nearly 400 years ago, but recently it has expanded enormously (see Figure 1.1A and B).

At the end of the nineteenth century, we did not know where we were, or where we came from; we did not even realize that we did not know it. The vastness of space and time had always been thought to be beyond any possible observation or experiment; in a word, their study was considered to be a part of *metaphysics*. Metaphysics concerns everything that *might* exist, but which we have no means of detecting. In contrast, the physical world is made up of what we can see, touch, hear, taste and smell, i.e. observe. In this sense it can be said that *angels* are a part of metaphysics, whereas a *chair* is part of the physical world.

Over the last 300 years, we have invented new means of detection that have extended our senses and give them 'feelers'. We have rolled back the limits of metaphysics more and more. Our detectors have recognized a number of invisible waves in the domain of the physical world. Although not seen, heard or felt, these waves have become so familiar that they are now part of our daily life: radio,

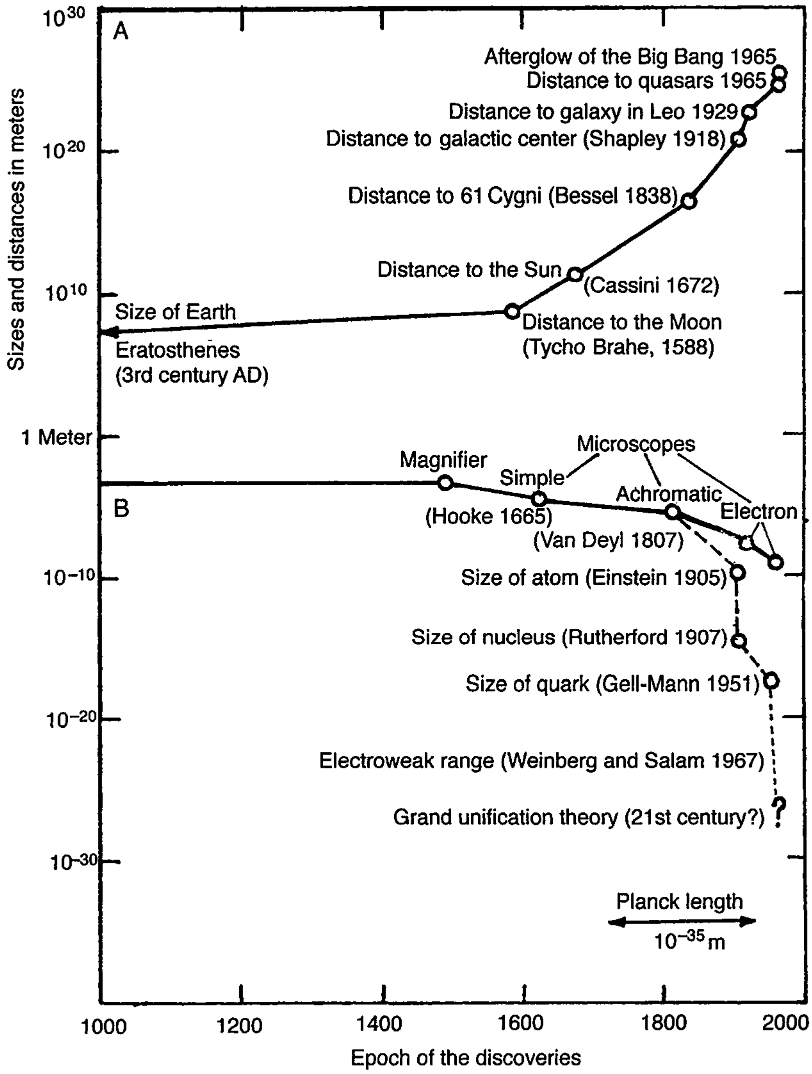

FIGURE 1.1 Exploration of (A) the extremely large and (B) the extremely small during the last millennium.

television, X-rays, gamma-rays, infrared and ultraviolet rays. We have probed the extremely distant as well as the extremely small with techniques that could not have been imagined three centuries ago.

Yet it would be naïve to believe that metaphysics is about to disappear. We still do not know nearly enough to guess at what is hidden by what is presently unknown. However, it appears that our inquiries have made sufficient progress to begin to perceive limits. These limits seem to exist in time as well as in space, in the extremely small as well as in the extremely large; they bring problems that we are not yet able to comprehend. For example, the extremely large is perhaps not infinite, in spite of being without limits. The infinitely small might not exist, since the extremely small is governed by strange laws which prevent us from going any further because they seem to defy common sense. Moreover, eternity does not seem to have existed in the past, because there was a 'grand beginning' before which there probably was no '*before*'. Time could also come to an end in the distant future.

Investigation of the distant past has led to the understanding that the Universe has not stopped evolving towards a growing complexity. This is a fundamental discovery that illuminates the human condition in a new light. From a beginning of extreme simplicity, the Universe has proliferated more and more complex structures, of which we are the outcome. The primordial explosion first produced elementary particles, then assembled them into light atoms, which formed the first stars. These stars cooked a great variety of heavy atoms in their cores, and then exploded, scattering the elements deep into interstellar space. These new atoms combined into the first grains of solid matter and the first organic molecules. Solid matter allowed the birth of planets such as the Earth; on such a planet, organic molecules brought all the chemicals needed for the emergence of life. Seen from this perspective, the growth in complexity of biological structures seems to follow the inevitable pathway of preexisting cosmic processes toward an ever growing sophistication. The biological evolution that so far has led to intelligence seems to be the consequence of those cosmic processes that started from the onset of a slight asymmetry.

Together we are going to try to reconstruct, step by step, the story of the Universe. It will lead us from the Big Bang, to the shaping of galaxies, then the condensation of stars in the midst of galaxies, to the cooking of most of the chemical elements in the heart of stars, and to their dispersal in interstellar space. I will describe the birth of the second-generation stars, which for the first time allowed the formation of rocky planets such as the Earth, and I will sketch the complex formation of our Solar System. We will discover the crucial role of the giant planets, which have deflected cometary orbits, so that comets will carry to Earth the organic molecules needed for the emergence of life. We will follow the long process of biological evolution on the Earth, and examine the ways and means by which astronomical and meteorological phenomena have shaped the incredible complex branching and pruning of the evolution of species. Thus we will come to understand how biological evolution and natural selection have finally resulted in human beings.

Needless to say, this history of the Universe still has many gaps. I will have to paraphrase and simplify, restricting myself to sketching only the main features. In spite of all these gaps, most known pieces of the puzzle seem to fall in place, so that we can make a reasonable guess at the whole picture, and the results seem extraordinarily promising. Before embarking on a chronology of the events in the whole Universe, it may be useful to recall the sizes and distances of the objects and structures that form the observable cosmos.

Let us first recall that, in spite of the great speed of light, the distances to be considered are so enormous that, when we look into them, we look into the past. On Earth, this past is indistinguishable from the present; at the speed of 300 000 km/second, light from a flash of lightning beyond the horizon reaches us in less than 1/10 000 second. But light already takes more than 1 second to reach us from the Moon, 8 minutes to come from the Sun, and 4 years from the nearest star. These times become incomprehensible for objects outside our Galaxy.

The light we see from the Andromeda Galaxy (barely visible to the naked eye) left there 2.5 million years ago; that is, long before the emergence of civilizations on Earth. The light from distant quasars left more than 10 billion years ago – a very long time before our Earth even existed. We do not see these objects as they are at present, but as they were at different times in the past.

I will begin this chapter by describing the general perception of the world three centuries ago. Then I will briefly explore, in measured steps, the depths of space. Finally, I will proceed in the same way into the microcosm revealed by present-day physics. This approach is needed if we are to understand the connections between elementary particles and cosmology at the beginning of the Universe.

Pascal's two infinities

Quantitative exploration of the Universe had barely started before the seventeenth century. In 1617, Johannes Kepler discovered that the square of the periods of the planets' revolutions around the Sun are proportional to the cube of their distances – known as Kepler's Third Law. Since Saturn takes about 30 years to make a circular journey around the sky before coming back to the same constellation, it was easy to compute that $30^2 = 900$, and conclude that the distance of Saturn from the Sun would have to be nearly ten times larger than that of the Earth (because $10^3 = 1000$). This enormous distance was difficult to accept, because it shattered antiquity's concept of crystalline spheres in the sky.

A little later, in 1672, the astronomer Jean-Dominique Cassini, who came from Italy to France, at the request of King Louis XIV, to start the Observatoire de Paris, was able to determine the scale of the Solar System through careful measurement of the distance from the Earth to the Sun. Dubbed the astronomical unit (or AU in short), this distance is approximately 150 million kilometers.

During the same period, Dutch naturalists were for the first time exploring the world of cells and microbes. Using the single-lens microscope (whose objective was a tiny glass ball) they could distinguish details of less than a hundredth of a millimeter. Thus, Jan Swammerdam discovered in 1660 the existence of red blood cells, while in 1674 Antonie van Leeuwenhoek discovered infusoria, bacteria and spermatozoa.

The educated people of the time were astonished by these discoveries and wondered what was hidden in the infinitely small and the infinitely large. Shortly before his death in 1662, the French scientist and philosopher Blaise Pascal wrote of this in his *Pensées*, published posthumously in 1670. In order to better appreciate the philosophical 'dizziness' arising from the human condition, he emphasized the 'disproportionality' of humankind in comparison with the two infinities, the infinitely large and the infinitely small. He first meditated on the immensity of the Solar System, just revealed at the time by Kepler's

Third Law. Although he did not know any stellar distance, he wanted us to feel the immensity of the depths of space:

> However hard we try to inflate our conceptions beyond imaginable realms, we give birth to atoms only at the expense of real things.

The discovery of the microscopic world by the Dutch naturalists amazed Pascal just as equally, since he insisted on the fact that the infinitely small hides 'another marvel just as astonishing'; he wished us to contemplate 'a new abyss' where we could see 'an infinity of universes, each with its firmament, its planets, its Earth . . .; on this Earth, animals . . .'. Pascal's grandiose vision still seemed prophetic 200 years later. In 1860 we still had no idea of the size of the atoms, and we had just attempted to measure the distance to some of the nearest stars.

The exploration of the extremely large and the extremely small began in earnest only in the twentieth century, and its results have been even more surprising than anything that the author of *Les Pensées* would have been able to dream of. First, the two infinities are in no way similar, because no structure repeats itself at the different scales. The atom has nothing to do with a Solar System in miniature, in contrast to its first primitive model, proposed by the Danish physicist Niels Bohr in 1913, but discarded in 1926 in favor of quantum mechanics. Of course, the natural laws remain valid for all scales, but their influence depends essentially upon the scale under consideration. For instance, gravity remains valid at the atomic level, but it is too weak to work effectively. The electromagnetic force prevails at the atomic scale, whereas at the still much smaller scale of the atomic nucleus, much stronger nuclear forces prevail.

For Pascal, the greatest surprise would probably have been that natural limits have been found for the extremely large as well as for the extremely small; we are not yet sure of the meaning of these limits. In the extremely large, there is the possibility (but as yet no certainty) that the Universe is not infinite, but could be without limits because the geometric structure of space–time would close it back upon itself.

And what about the 'Big Bang', the explosion that is thought to have started the whole Universe? The theory of the Big Bang clarifies and explains the cause of a number of observational results that would otherwise remain mysteries.

The existence of the Big Bang introduces a natural limit, not only for the time elapsed, but also for the volume of the Universe accessible to observation, because of the finite speed of propagation of light. At that distant time in the past, the enormous heat of the Big Bang made all space as bright as the surface of our Sun. It is the afterglow of this light, shifted to millimeter wavelengths by the expansion of the Universe, that we detect in the depths of space. In a way, it is an impenetrable veil that hides from us the first moments of the Universe.

On the other hand, for the very small, the study of the world of quanta has revealed a haziness inherent in the nature of things; it arises from the discrete structure, both wavelike and corpuscular, of all particles of matter and of radiation. This fundamental haziness implies in particular that, in order to detect smaller and smaller particles, we must bombard them with other particles moving at higher and higher speeds. Among physicists, this has spurred a rush to create larger and larger particle-accelerators, operating at higher and higher energies (and with more prohibitive budgets!).

Thus, we now glimpse a perhaps finite Universe, but more extended than anything Pascal would ever have dreamed of, made up of elementary particles smaller than any he would have been able to imagine, but perhaps still limited by the structure of space itself, which we are only beginning to try to understand.

In the following sections, since we must feel comfortable with imagining structures of prodigiously different dimensions, I am going to give a brief summary of the scale of objects in the Universe. To avoid the bewilderment caused by large numbers, I will move up or down by reference steps. But the steps themselves must not be too big; whenever possible, I choose a factor close to 10 000. This factor represents reasonably well the limit of our perceptions without the help of any instruments. Indeed, 10 000 steps take us just to the horizon, while a ten-thousandth of a meter (0.1 mm) is the ordinary limit of the resolving power of the human eye.

For our ascent (or descent) there is fortunately a hierarchy of structures to help us.

Ascent to the extremely large

First step: the mountains (10^4 m = 10 km)

The meter is appropriate to the size of human beings; 10 000 m (10 km) takes us beyond the horizon or, if we travel upward, a little higher than the highest mountains. Ascending a very high mountain already gives us the feeling of the smallness of humans and of our insignificance with regard to nature. And thus I have just described the scope of primitive peoples. The nomadic hunter living on a hunting territory (some scores of square kilometers) could not comprehend the size of the Earth – the next step.

Second step: the planets (10^8 m = 100 000 km)

The size of the Earth was successfully assessed for the first time by Eratosthenes of Alexandria in the third century AD. He measured the shadow cast by a vertical stick in Alexandria, at the moment when he knew that the Sun was vertically overhead at Aswan in Upper Egypt. He concluded that the angle separating the two verticals was 1/50 of the circumference. Since the two cities were 5000 stadia apart, he deduced that the circumference of the Earth measured 50 × 5000 = 250 000 stadia. The stadium was the field where the Greeks practiced sports; examination of the ruins of ancient Greece shows that its length was approximately 160–170 m. Eratosthenes' result was close to the correct value, since 250 000 × 160 m = 40 000 km, the Earth's circumference. With its diameter of about 13 000 km, the Earth is a very modest planet. A giant planet like Jupiter has a diameter 11 times as large (140 000 km).

Third step: the giant stars (10^{12} m = 6.7 AU)

When he defined the astronomical unit (AU) as the mean distance from Earth to Sun, Cassini also estimated the diameter of the Sun: about 1 400 000 km or 0.009 AU. The luminosity, distance and diameter of the *red giant* stars was determined only in the twentieth century, by the use of the Cepheid stars. Some of the red giants have diameters larger than the distance from the Earth to the Sun. Betelgeuse, for instance, a red giant in the Orion constellation, has a diameter of 4 AU. By and large, red giants are stars at the end of their evolution. When they have transformed most of their core's hydrogen into helium, the core collapses upon itself and rises to a much higher temperature. Radiation from the central core becomes so intense that it blows out and distends the outer layers of the star to the enormous observed diameter.

Fourth step: the Solar System (10^{16} m = 1 light-year)

The light-year (l.y.) is the distance travelled by light in one calendar year, at a constant speed of 300 000 km/second; it is equal to 63 000 AU. The planetary orbits are all concentrated within a tiny zone of 50 AU radius around our Sun, but the attraction of the Sun dominates to a distance at least 1000 times larger, as shown by the 100 billion comets present in the Oort cloud. Although not detectable from Earth, the presence of the Oort cloud is demonstrated each year by two or three 'new' comets detached from it by galactic tides. The existence of the Oort cloud surrounding the Sun fixes the size of the Solar System at more than 1 l.y.

Distances to neighboring stars are also included in the fourth step, because they are only a few light-years away. The German astronomer Friedrich Bessel determined the first distance to a star in 1838, by measuring the parallax of 61 Cygni. Parallax is the angle through which the star appears to oscillate over one year against a background of distant reference stars, because of the yearly motion of the Earth around the Sun. Bessel found that 61 Cygni oscillates around its mean position by 0.30″ (3/10 of a second of arc) which corresponds to a distance of 11 l.y. Comparison of a few bright stars showed later that the parallax of Proxima Centauri was the largest, so that this star was the nearest to the Solar System. Since the parallax of a star diminishes as its distance increases, parallaxes can be measured, but with less and less precision, up to distances of about 1000 l.y., thanks in particular to the recent observations by the European satellite Hipparcos.

Fifth step: the galaxies (10^{20} m = 10 000 l.y.)

In 1610, when Galileo turned his first astronomical telescope toward the Milky Way, he discovered to his amazement that this milky ribbon, barely visible across the sky on moonless nights, is actually a collection of stars too faint to be seen individually with the naked eye. In 1780, the Englishman William Herschel proposed that the Milky Way is actually a disk composed of millions of stars. We can see this disk from within because our Solar System is inside and part of it.

In 1918, the American Harlow Shapley determined that our distance from the center of this enormous system of some 600 billion stars was about 25 000 to 30 000 l.y. It was only after the Second World War that radioastronomy finally detected the spiral structure of the immense arms of interstellar hydrogen which are part of the Milky Way. This demonstrated its similarity to numerous spiral-form galaxies seen in all directions in the depths of space.

The Milky Way is our Galaxy. It is a giant galaxy, ten times as large as the average. The size of our fifth step coincides with the average diameter of the multitude of small galaxies.

Sixth step: the clusters of galaxies (10^{24} m = 100 million l.y.)

Far out in the depths of space, we see that the galaxies are not uniformly distributed. They spread out in irregular groups separated by enormous distances of totally black space. In particular, our Galaxy is part of a group of some 30 galaxies; this is the so-called *Local Group*. The two giant galaxies of the group are ours (diameter 100 000 l.y.) and that of Andromeda (130 000 l.y.), which is 2.5 million l.y. from us. There are also four or five galaxies of average size, like M33 in the Triangle (diameter 60 000 l.y.), the two Magellanic clouds (30 000 and 15 000 l.y.) plus a good score of small galaxies (all less than 10 000 l.y.). These 30 or so galaxies are all contained in a quasi-spherical volume of the order of 4 or 5 million l.y. in diameter. Our Galaxy is near the periphery, while the Andromeda Galaxy is at the center. Variable giant stars like the Cepheids as well as novas are still distinguishable individually in the Local Group, and this permits measurements of sizes and distances in the group.

Our Local Group is a very small cluster of galaxies. The richest of the next clusters of galaxies is the Virgo Cluster, consisting of at least 2500 bright galaxies. Within it, the Hubble Space Telescope (HST) detected in 1992 numerous bright blue individual stars, confirming that its distance is close to 50 million l.y. This was an important measurement, because it served to calibrate larger distances and, from