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ENRICO PREDAZZI

What is the Universe Made Of?

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What is the Universe Made Of?

ENRICO PREDAZZI

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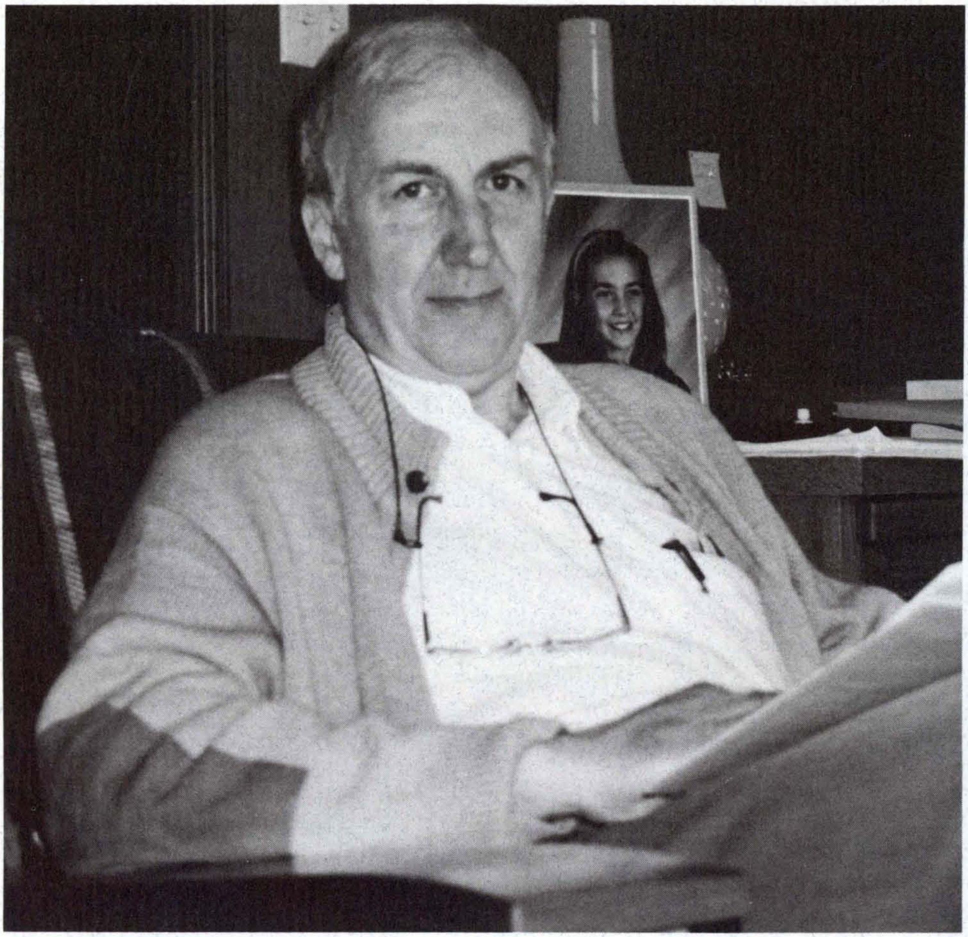

Professor Enrico Predazzi, former Director of the Department of Theoretical Physics at the University of Torino, Italy, is an internationally known author of three books and more than 200 research papers in theoretical and mathematical physics. He has made outstanding contributions in making models to describe the results of high-energy collisions of elementary particles. He has been concerned with elastic scattering, with inelastic scattering, and with the production of a whole variety of new particles, most of which decay in less than one-millionth of a second after they are created. Professor Predazzi has also worked on understanding the structure of atomic nuclei and of the protons and neutrons which are the constituents of nuclei. He has consistently spread knowledge about elementary particle physics to others in his field and outside it. As well, he has given to experimentalists considerable insight into the critical measurements that need to be made to test current models and theories.

ENRICO PREDAZZI

WHAT IS THE UNIVERSE MADE OF?[1]

> The Universe?
> This epic mystery story has not yet been resolved.
> We are not even certain that it has a definite solution . . .
>
> -Albert Einstein

Amusingly enough, we do not know what kind of matter an estimated 90% of the universe is made of, although there are lots of hypotheses. However, we have a name for this unknown stuff: we call it dark matter. Somebody said that once you give a name to something you don't know anything about, you feel much better, almost as if you have solved the problem. The situation is well summarized by Bernard Sadoulet:

> It will be the ultimate Copernican revolution: not only are we not at the center of the universe, but we are not even made up of the same stuff as most of the universe. We are just this small excess, an insignificant phenomenon. The universe is something entirely different.

Thus, even if I take some time to discuss the various hypotheses about dark matter, I will probably spend most of my time talking about that 10% of matter that we actually know something about and that I will call *luminous* matter.

Just to set the scale, the universe has been around for quite a while (between 10 to 20 billion years) and has a respectable size (something like 10^{28} centimeters (cm); i.e. its boundaries are some 2-4 billion times farther away than the star closest to the solar system). Because of the vast size of the universe, physicists often use large units of distance when talking about it. A convenient unit of distance depends on the great speed of light, the largest speed at which a signal can be transmitted. A *light-year* is the distance light travels in one year, or about 10^{18} cm. (Another unit often used is the parsec, which is 3.26 light years.) The speed of light is 300,000 kilometers/second, so a distance of 300,000 km is one

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[1]This lecture was given in Bloomington for the Indiana University Institute and Society for Advanced Study on September 24, 1993.

light-second. The moon is a little more than a light-second away from us. The sun is eight light-minutes from us. The nearest star is about 4 light-years away, or about 280,000 times the distance between us and the sun.

It is well known that the distribution of visible matter in the universe is not uniform but is concentrated in stars, which, in turn, are mostly in galaxies. Moreover, the galaxies are also clustered. Our own galaxy is called the *Milky Way*. Another galaxy in our local cluster, much like our own, is the Andromeda galaxy, which appears as a fuzzy object in the sky.

The universe is not static, but is expanding in such a way that distant galaxies are rushing away from us at speeds very nearly proportional to their distances from us. The speed at which Andromeda is fleeing from us is probably between 40 and 80 kilometers per second. The expansion of the universe is known as *Hubble's law*, and the rate of expansion is known as *Hubble's constant*. The present theoretical description of the expanding universe is given within the framework of Einstein's theory of general relativity.

The average density of the *visible* (luminous) matter in the universe is estimated to be just a few per cent of the value 10^{-29} gram per cubic centimeter (roughly equivalent to 10 hydrogen atoms per cubic meter of space) which, according to calculations in general relativity, would be necessary to eventually halt the above expansion. As we will see later, the mystery of dark matter is linked to the fate of the universe or, more precisely, to the basic question of whether or not the parts of the universe which are presently flying apart will ever fall back together.

Everybody "knows" that the universe began with a *Big Bang*; there are good reasons to believe this, like:

i) *Hubble's law* (1929), which denotes the expansion of the universe;
ii) the cosmic background radiation filling the whole universe (1965), which is considered one of the smoking-gun signatures of the *Big Bang* theory; and
iii) the abundance of light elements (we will briefly discuss this later).

What is much less clear is *how* the *Big Bang* occurred or, even less, *what* made it occur. Several schools exist, almost all of them invoking a superior entity called *God* to act as the Creator; we have, I fear, no way to test any of these conjectures scientifically. There are, however, also attempts to relate the *Big Bang* to purely physical phenomena such as a *fluctuation of the quantum vacuum* whereby, due to specific properties of quantum mechanics, it is conceivable that, at some point, some positive energy (a physicist would call it *kinetic* and *rest* energy) and an equal amount of negative (or *potential*) energy could have become separated emerging from the vacuum. Unfortunately, nobody has, as yet, been able to produce a specific mathematical model of how this could have happened.

In recent years something in one way quite unexpected but in another way rather natural has occurred. This was the recognition that the world of the exceedingly small (the world of particle physics), and the world of the exceedingly large (the universe) are closely related to each other. To be more specific, laws of nature discovered while investigating the world of particle physics play an important role in the details of the development of the universe.

In the particle-physics world, typical sizes range from 10^{-13} cm, which is the size of the smallest nucleus, down to less than 10^{-18} cm, which is the experimental upper limit on the size of the electron.[2]

As a consequence of the connection between the worlds of the very small and of the very large, many particle physicists have become interested in cosmology and, conversely, most cosmologists have become conversant in particle physics. This is due to several facts. On the one hand, particle physics provides a large number of *natural* candidates (if anything, too many) to explain dark matter (but candidates of conventional matter also exist). On the other hand, the collisions among particles occurring in the biggest accelerators are the closest analog of the *Big Bang*. Performing and interpreting experiments on these accelerators allows us to obtain information about laws which influence the development of the universe starting from an extremely short time after the *Big Bang* occurred. Laws of particle physics have enabled us to calculate such things as the temperature of the background radiation and the synthesis of the chemical elements. The largest accelerator in the world, which was to be constructed near Dallas, Texas, the so-called Superconducting Super Collider or SSC, would have led us to better understand phenomena that happened some 10^{-13} seconds after the *Big Bang* occurred (see Figure 1). Figure 1 shows an overview of what is today believed to be the succession of events which followed the *Big Bang*.

So, in spite of their being at opposite ends of the human frontier of knowledge, the merging of particle physics and astrophysics into what could be called *astroparticle physics* has been useful in the past and promises to be even more fruitful in the future.

It is astonishing that contemporary physicists and cosmologists of Western civilization have returned to essentially the same philosophical and scientific questions and speculations which were raised for the first time by the Greeks

[2]The study of nuclear structure goes back to the pioneering work of the American physicist Robert Hofstadter in the 1950's which earned him the Nobel prize in 1961.

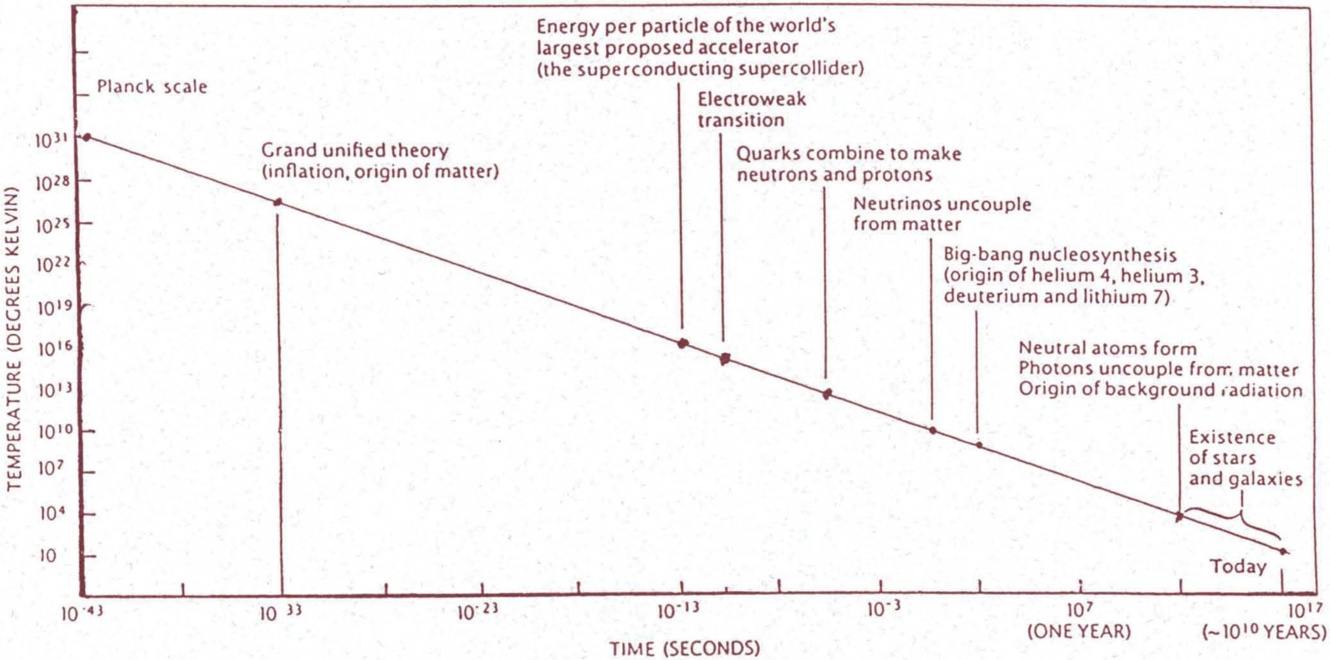

Figure 1 - Schematic evolution chart from the *Big Bang* to today.

more than 2500 years ago. I could summarize these developments by enlarging the title of this talk to:

What is the universe, and what are we made of?

It was Bertrand Russell who stated that in the entire history of mankind, nothing is so extraordinary as the sudden explosive growth of civilization in Greece.

It is not accidental that we still use today the Greek word *cosmos* (whose meaning in Greek is *order*) to refer to the universe. The word *cosmogony* is commonly used to refer to ancient ideas about the origin and structure of the universe, whereas the word *cosmology* is used for contemporary investigations.

At about the same time (600 to 400 BC), Greek *lovers of wisdom*, i.e. philosophers started asking about both the properties of the universe and the inner composition of matter. One school decided that matter was made of fundamental building blocks, from which the word *atom* (whose meaning is: *indivisible*) comes. (Also at about this time the Greeks began to investigate electricity and magnetism). Perhaps it is not accidental that the same questions became popular again during the last century. Although our knowledge has progressed tremendously, the final answers to these questions are still wanted.

Returning to the title of today's talk, it is instructive to go back to answers given originally by the Greek philosophers. In particular, we will discuss some ideas of the Milesian school, which flourished from the time of *Thales*, its founder (who is credited with having predicted a solar eclipse in the year 535 BC), of *Anaximander* (who was alive in the year 546 BC) and of *Anaximenes* (who was active in the year 494 BC).

Thales believed in a primordial substance from which everything is derived. He assumed that this substance is *water*. Inasmuch as all living creatures are mostly (say 70-90%) made of water and the latter was considered an element until 1781, this was not an absurd idea.

Anaximander also believed that everything comes from a primordial substance which he called *the unlimited* (το απειρον), but that it is neither water nor any other substance we know. He believed it to be infinite, eternal, and to make up all the worlds of which ours is just one of many. According to *Anaximander*, within the *unlimited*, something arose to produce the opposites of *hot* and *cold*. They began to struggle with each other and produced the cosmos. The *cold* (and wet) partly dried up, becoming solid *earth*. Part remained as *water* and, by means of the *hot*, part evaporated to become air. The evaporating part, by expansion, split into *fire*. All bodies result from the combination of these four elements which are seen as sort of *gods;* each of them tries to dominate the others but their proportions in various materials follow from a certain necessity. It is from these proportions that the *laws of nature* result.

According to *Anaximenes,* the primordial substance is air; the *soul* is nothing but air. Neither *Thales* nor *Anaximander* appear to have specified the way in which the other things arose out of the water or of the *unlimited*. *Anaximenes,* however, maintained that all other types of matter arose out of air either by condensation or by rarefaction. *Fire,* he claimed, is rarefied air which, when condensed, becomes *water;* the latter, by further condensation, gives rise to *earth*.

The above ideas can be regarded both as the first known attempts to answer *what we and the entire universe are made of* as well as a pioneering attempt to introduce forces of cohesion. These forces are viewed as a sort of *respiration*. Just as our soul, made of air, keeps us stable, a universal respiration insures the cohesion and stability of the whole universe. Something similar occurred in the 19th century, when the role of the *air* was replaced by that of *ether*, which was made responsible for transmitting physical actions.

In emphasizing the remarkable Greek contributions to philosophy and science, we should not ignore that elements of scientific development were present much earlier in other civilizations, such as the Egyptian, the Mesopotamic, the Chinese and the Indian. For instance, we owe to the Chinese the oldest recording of a *nova* star (Figure 2) (about 1300 BC), elaborate descriptions of the impact of a celestial body on earth, the oldest printed map in the world, etc. Also, the Indian and the Chaldaean civilizations had cosmogonies of their own (Figure 3).

As far as I know, in all other ancient cultures, scientific developments were motivated either by practical considerations (such as the study of the sky to understand the cycle of the seasons), were purely observational, were a mixture of religion and science, or had a strong anthropomorphic component. It is the lack of these biases that led *Bertrand Russell* to consider the cosmogony of the Milesian school as the first example of a truly scientific hypothesis, since it is neither motivated by ethical principles nor does it contain anthropomorphic considerations.

It may be instructive to notice at this point that the modern physical view is *conceptually* not so distant from the Greek, at least concerning the idea that everything is *made up* of basic constituents. Perhaps we have reached a different level of sophistication, and, instead of talking about *air, earth, fire and water* we talk about *leptons, quarks, photons, gluons etc.*, which are now regarded at the fundamental particles of nature. However, the basic philosophy is quite similar;

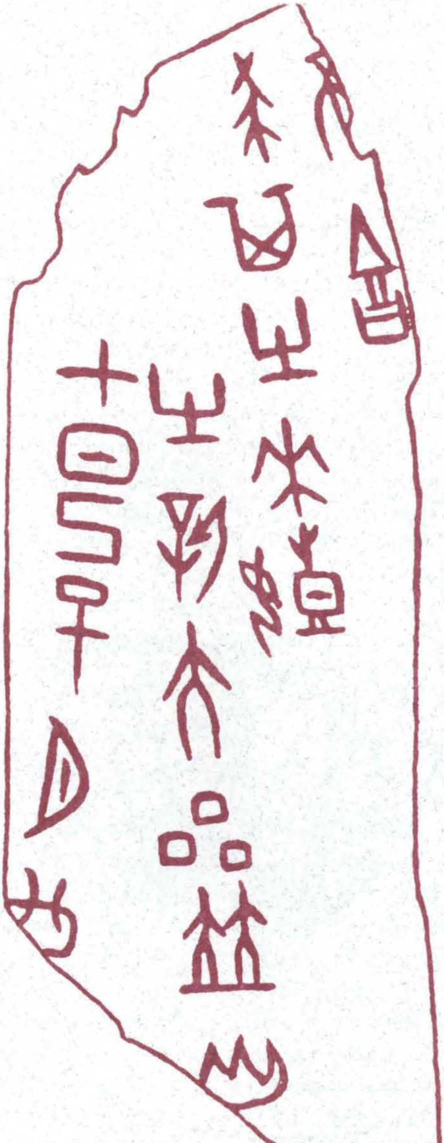

Figure 2 - The oldest record of a nova. The inscription on this oracle-bone dates from about 1300 B.C. and, in the two central columns, states that ". . . a great star has appeared in company with Antares."

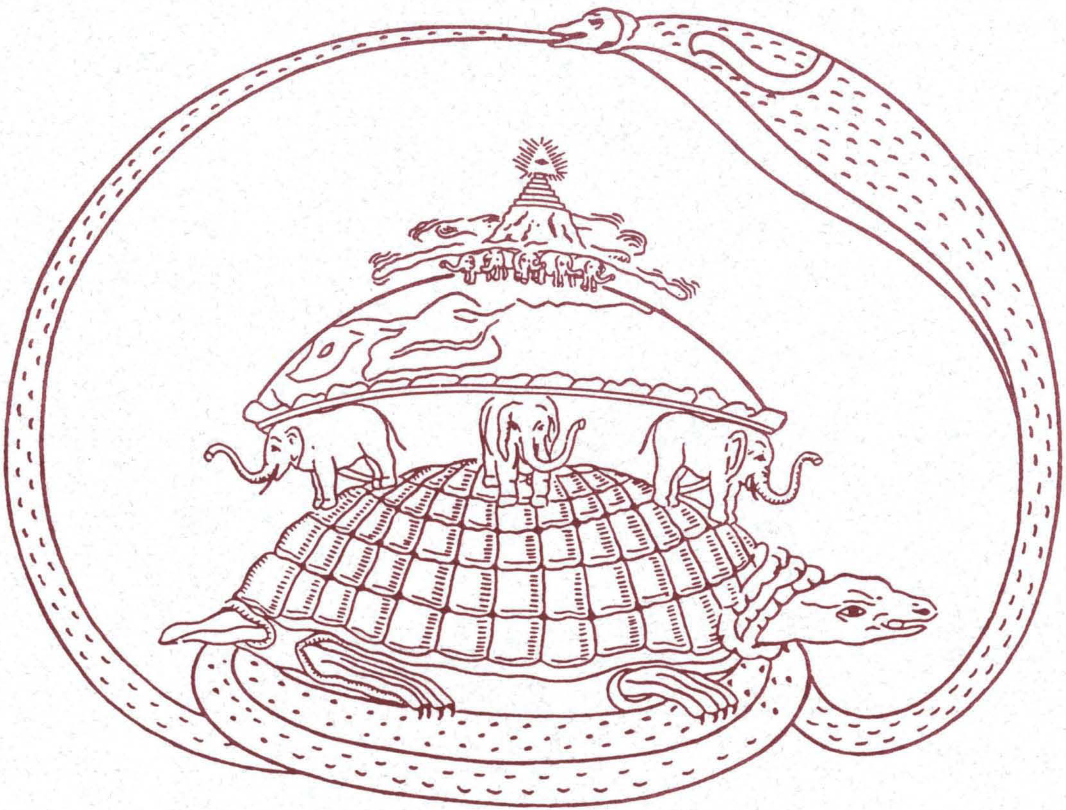

Figure 3 - The Hindu cosmogony. The world is supported in the vacuum by a huge snake on which stands a giant turtle. The latter supports three elephants holding the Earth. Other elephants support the tallest mountain in India with seven steps (the Seven Skies, residence of the gods) and a triangle symbol of the Creation.

the result is a *cosmos* (remember, the word means *order*) in terms of which all matter *known to us*, including *intelligent* matter, can be explained in physical terms. It is this intelligent matter which is trying to study the universe and marvels that it is (to some extent) understandable.

We owe to *Pythagoras* the use of the term: *theory*. The term means *a state of contemplation*, which is at the origin of mathematical and physical developments. To him, we also owe the idea that *everything is number*. After *Galileo, Newton, Maxwell, Einstein and Dirac* (to mention just a few of the great physicists), this idea has become quite familiar to modern physicists in the sense that modern theoretical physics can often be cast in a beautiful mathematical form (so beautiful that sometimes people lose contact with the physical reality).

To proceed with our brief historical discussion of the Greek cosmogony, we cannot ignore *Heraclitus*, who believed in a unique primordial substance resulting from a combination of the four basic elements. More important, he believed in a single unity made of all things and that all things are derived from one single unity. In his words, the basic notion is: παντα ρει (*everything flows*); mortal beings are immortal and immortals are mortal. This may sound crazy, but modern physics teaches us that photons die, producing particle-antiparticle pairs and, conversely, are produced by the annihilation of particles with antiparticles.

The Greek cosmogony, still in embryo as expressed in one of *Plato's* dialogues, reaches its highest point in *Aristotle*, whose *credo* influenced western science and philosophy so much as to become, 2000 years later, a serious impediment to progress. The formal elegance of *Aristotle's* philosophy, however, is extraordinary and is reflected in the astonished look of the experimenter shown in Figure 4.

According to *Aristotle*, there are two kinds of motion, that of terrestrial bodies and that of celestial bodies. The sky is made of concentric spheres, of which the sphere of the *Moon* has the smallest radius and the *Earth* is at the center. Everything below the lunar sphere is corruptible and perishable. The celestial bodies have a regular behavior which obeys God's designs. The succession of spheres continues with *Mercury, Venus, Sun, Mars, Jupiter*, and *Saturn*, beyond which are the fixed stars culminating in the *Primum Mobile*. Beyond the *Primum Mobile* there is neither movement nor time nor places. There, *God*, the *Primordial Motor*, is standing and sets in motion the *Primum Mobile* from which the motion gets propagated to the lower spheres until it reaches the *Moon*. Figure 5 gives a medieval realization of such a cosmogony, whereas a curious variation is shown in Figure 6. The vacuum does not exist for *Aristotle* (*Horror vacui*), because in a vacuum, as in geometrical space, there are no special places or directions.

Figure 4 - An observer marveling at the harmony of the universe.

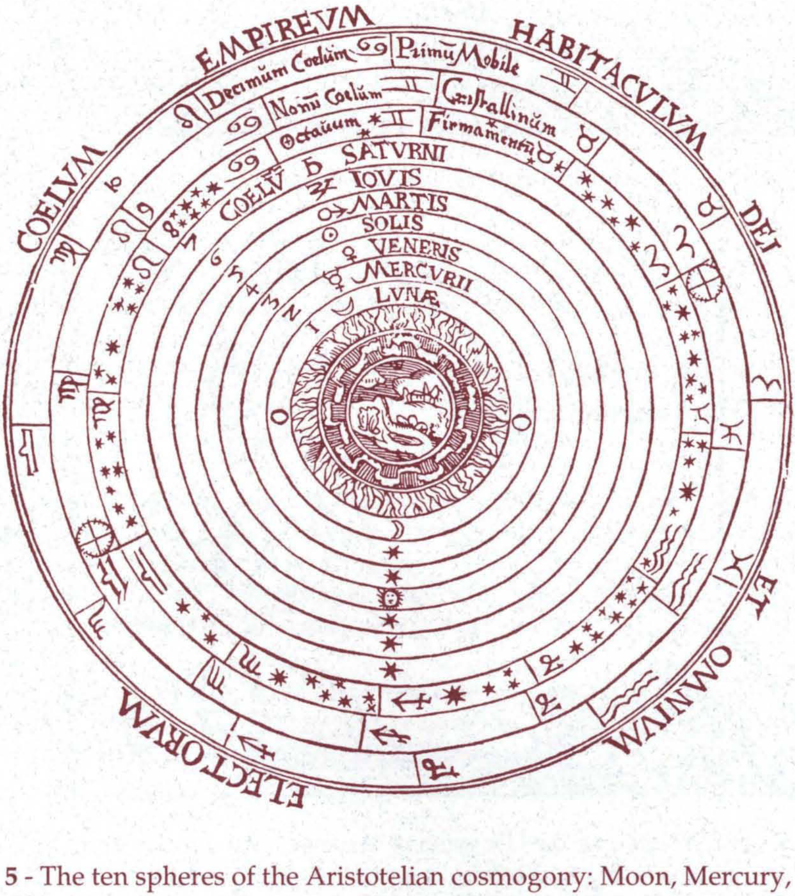

Figure 5 - The ten spheres of the Aristotelian cosmogony: Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn, the Octavum Coelum Firmamentum, the Nonum Coelum Cristallinum and the Decimum Coelum: Primum Mobile beyond which is the Coelum Empireum Habitaculum Dei et Omnium Electorum (The Empyreal Sky, Residence of God and of all the Elects).

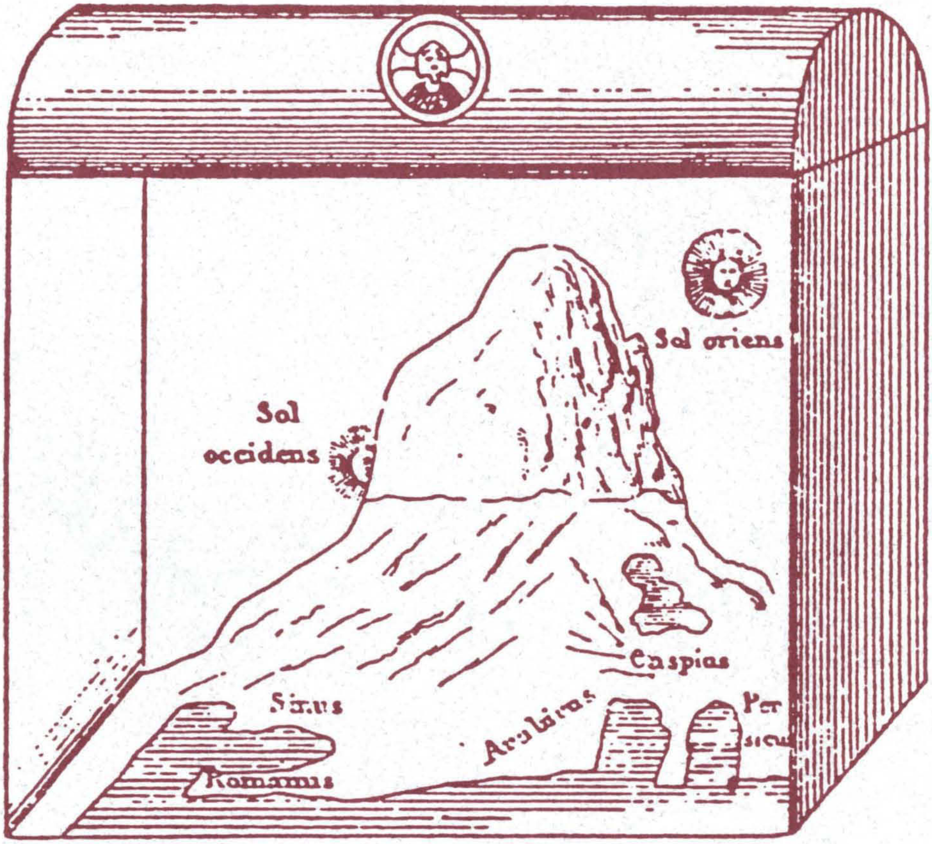

Figure 6 - The World and the Universe in the system of Cosmos Indicopleustes (6th Century). The rising and setting sun moves round the giant mountain in the north to produce days and nights. The Mediterranean, Red Sea and Persian Gulf are shown below, the heavens are in the form of a barrel vault: within them, the Creator surveys his works.

Aristotle's conception was later adopted by the Roman Catholic Church and led to the description of the *Paradise* made by *Dante* in *La Divina Commedia*.

In 1543 *Copernicus* displaced the *Earth* from the center of the universe, below the *Paradise*, and made it an insignificant point in space. In 1609 and 1619, *Kepler*, formulating his basic laws of planetary motion, destroyed the hierarchy of the celestial spheres. In 1609 *Galileo*, with his telescope, discovered new celestial phenomena, such as sun spots, outside the perfect Aristotelian model. Some scientists at the time refused to believe what they were seeing or dismissed their observations as *mere images* with no connection to reality. The disagreements went on until *Isaac Newton*, in the *admirabiles anni* 1666-67, laid down the foundation of modern physics, on which *Galileo* had earlier made such a noble beginning.

In contradiction to the teaching of *Aristotle*, *Newton* included both heavenly and earthly motion in a *universal* law of gravity. In 1686-87 *Newton* published his great scientific work, the first modern scientific treatise: *Philosophiae Naturalis Principia Mathematica*.

To clarify the issue of what exactly was so new in *Galileo* and *Newton* as compared with the previous developments, it is simplest to quote *Roger Newton* in his book, *"What Makes Nature Tick?"*:

> The main reason for crediting Galileo and Newton with the origin of modern science is that they based their search for knowledge of nature on observation and experiment and did not believe that such knowledge could be gained by pure thought alone. This was their revolutionary advance over their Greek intellectual predecessors.[3]

Isaac Newton, however, in spite of (or because of) his extraordinary achievements, was not much interested in trying to explain what made the universe but rather in achieving a reliable description of the movements of its bodies. As a consequence, the account he gives of how he viewed the atoms is still very unsophisticated.[4]

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[3]Cambridge, Mass. and London, England: Harvard University Press, 1993, 11.

[4]Towards the end of his treatise *Opticks*, he wrote ". . . it seems probable to me that God in the beginning form'd Matter in solid, massy, hard, impenetrable, moveable Particles, of such Sizes and Figures, and with such other properties, and in such Proportion of Space, as most conduced to the End for which he formed them; and that these primitive Particles being Solids, are incomparably harder than any porous bodies compounded of them; even so hard as never to wear or break in pieces; no ordinary Power being able to divide what God himself made one in the first creation."

The important lesson to be learned from the above sketchy discussion of ideas about the heavens (i.e. the universe, in today's language) is that the curiosity to understand it and to describe it has always been a tremendous driving force behind human efforts. The attraction to discover its secrets has never faded and is found everywhere, among people of the neolithic period (like *Stonehenge* in southern *England*) as well as among the Greeks, among the *Borneo* tribesmen and among people of the Renaissance (Figure 7).

The study of the universe has reached its extreme sophistication with the giant telescopes of modern times and even more with radio telescopes like *Arecibo's* (Puerto Rico) radio telescope (305 meters). In recent times, combinations of radio telescopes, such as the *Very Large Array*, have provided remarkable information. *The New York Times* reported recently the completion of the new combination of radio telescopes such as the *Very Long Baseline Array*, whose system of antennae spreads from *Hawaii* to the *Virgin Islands* for 5000 miles (Figure 8) and is expected to produce high precision images 1000 times better than those of the best optical telescopes.

The above instruments, however, are sensitive to the detection and study only of the *luminous matter, i.e.* of the conventional matter which we investigate in normal laboratories. In the 1930's, however, an important step occurred, the realization of the significance of dark matter, which radically changed the traditional perspective and which raised what remains today the most exciting question in astrophysical studies.

The concept of dark matter is not very new in astronomy, either as an idea or as a linguistic term. As for the idea, in 1844 *Bessell* deduced the existence of *invisible* companions of the stars *Sirius* and *Procyon*, which were not discovered until 18 and 41 years later respectively. Not luminous themselves, their presence was revealed by their gravitational effects on the luminous bodies.

As for the term dark matter, in 1922 *Kapteyn* observed that stellar velocity distributions give us a *means of estimating the mass of dark matter in the universe.* Eleven years later, *Zwicky* analyzed the velocities of individual galaxies within the cluster of galaxies known as *Coma*. He concluded that many of these galaxies are moving so quickly that the cluster as a whole should break apart unless there is much more mass to hold it together than the luminous mass alone. Here again, it is the gravitational effect which betrays the existence of otherwise undetectable matter.

Today, the best established evidence of dark matter is based on rotational velocities of spiral galaxies.[5] In these cases, the presence of dark matter is

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[5]One can, however, estimate the amount of dark matter through other *dynamical* methods such as using the *virial theorem* or by taking into consideration clusters of galaxies rather than individual ones.

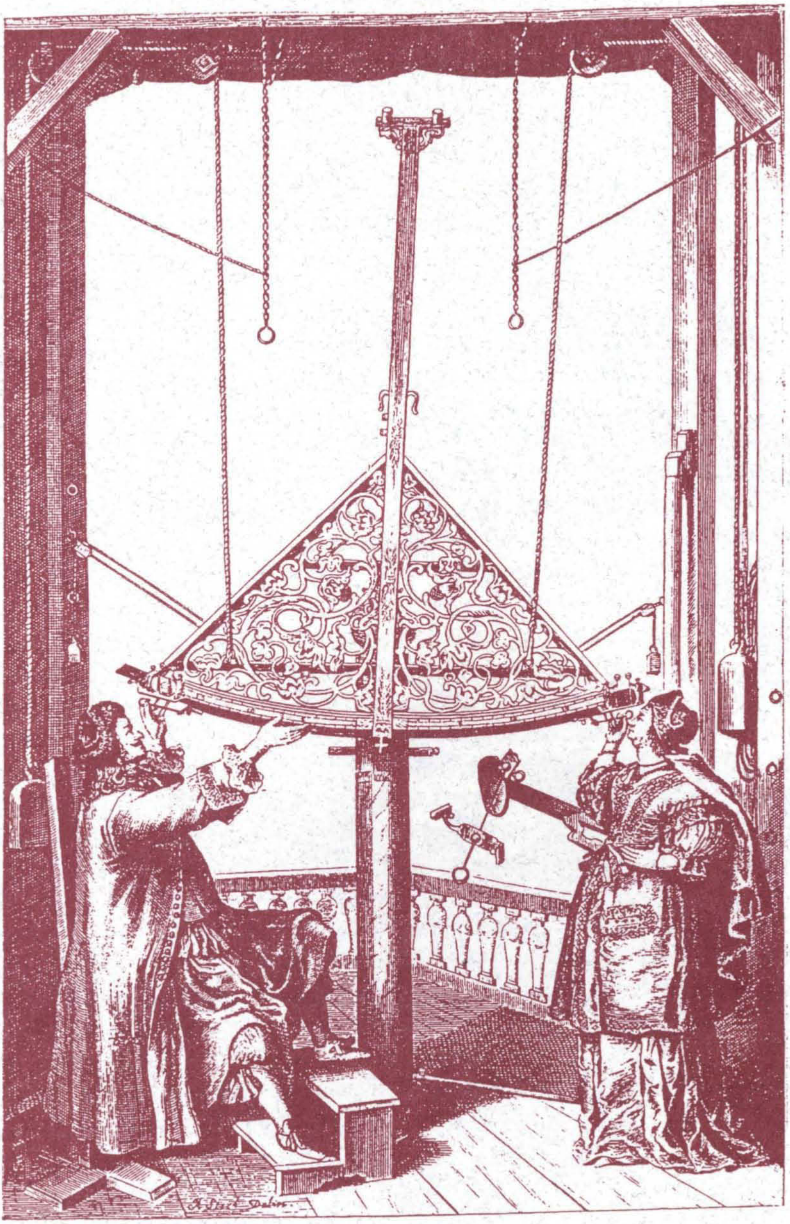

Figure 7 - The "Machina Coelestis" used by J. Höwelcke (alias J. Hevelius, 1611-1687) to study the position of the stars. He compiled a catalogue of 1564 stars.

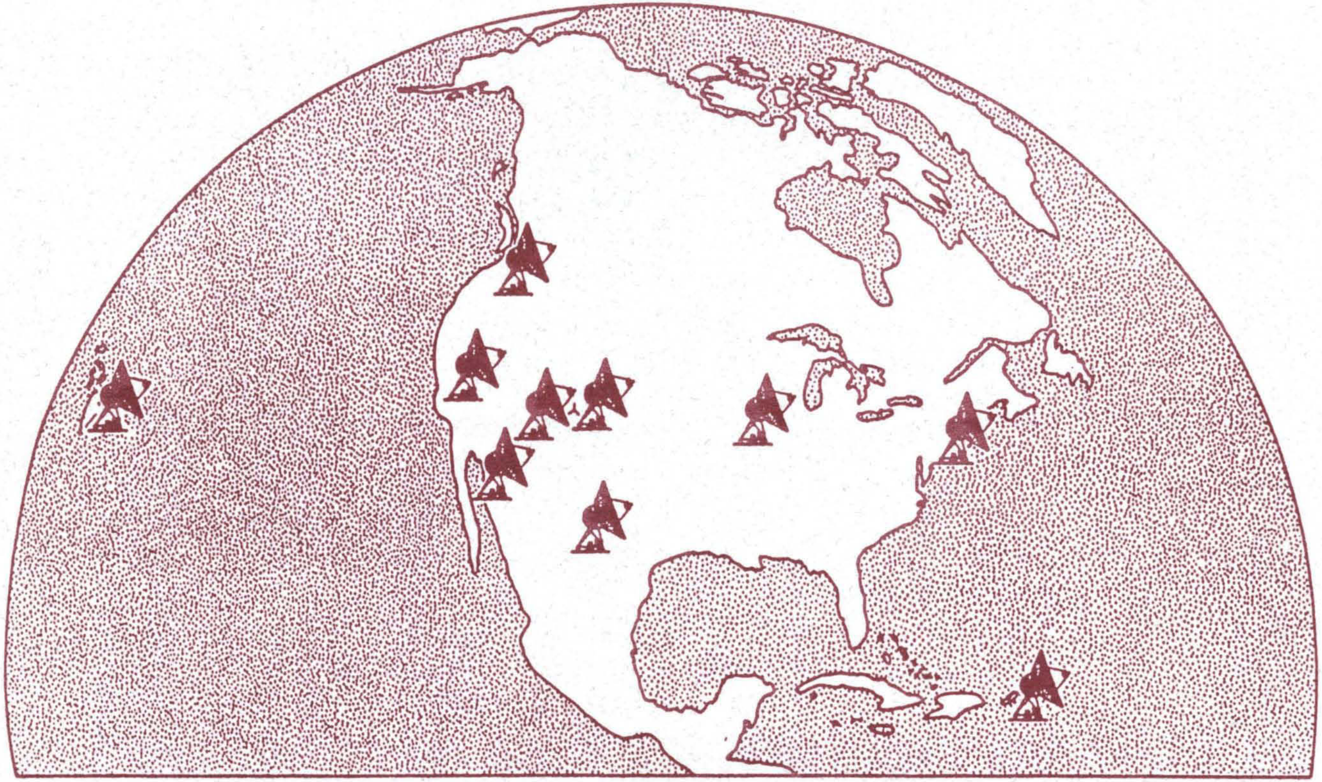

Figure 8 - The ten new antennas of the Very Long Baseline Array telescope spread from Hawaii to the Virgin Islands (5000 miles).

revealed by the motion of the outer arms. They are rotating about the galactic center faster than they would be expected to if the galaxy's luminous matter represented most of its mass. As an example, Figure 9 shows the discrepancy between the observed rotation curve in the outer region of the galaxy named NGC 2403 and the curve predicted theoretically. At large distances the curve becomes dominated by the dark matter contribution.

Without going into technical detail, it is, however, possible to understand qualitatively the importance of dark matter.

Everybody knows that matter attracts matter: the moon does not escape from its orbit around the earth because the latter exerts an attraction which is strong enough to prevent it. This attraction is, of course, reciprocal. The same holds true for the earth and the sun or, for that matter, the general equilibrium of celestial bodies. In fact, as we recall, this *cosmos* led in the first place to the cosmological system developed by the Greeks, which we briefly described above.

It is important to stress that gravitational attraction is proportional to mass; the larger the mass, the stronger is the attraction. When the amount of mass in a certain volume exceeds a certain calculable value, the theory of relativity says that the gravitational attraction causes the body to collapse. In an extreme situation the collapse produces what is known as a *black hole*, a body from which no light can emerge. A black hole is a kind of sink into which matter disappears except for its gravitational effect, which remains.

The amount of attraction between the various parts of the universe depends on its *density*, that is, on how much mass the universe contains per unit volume. Depending on the density, the universe either will continue to expand indefinitely, the expansion will progressively slow down until it stops infinitely far in the future, or a time will come when the expansion will come to a halt and the universe will start to contract. These various possibilities are usually referred to as an open (i.e. *expanding*), a *flat* (*i.e. expanding but at a decreasing rate)* and a *closed (i.e. contracting from some time on*) universe.

The discriminating parameter of the universe is known as the *critical density* ρ_c. According to whether the actual density of the universe ρ is smaller, equal, or larger than the critical density, the present expansion will continue forever, will slow down to stop asymptotically (infinitely far in the future), or will at some time start to contract.

The critical density can be expressed in terms of the *gravitational constant* G appearing in *Newton's* law of attraction and the *Hubble* constant H_0. The relation is:

$$\rho_c=3H^2_0/8\pi G$$

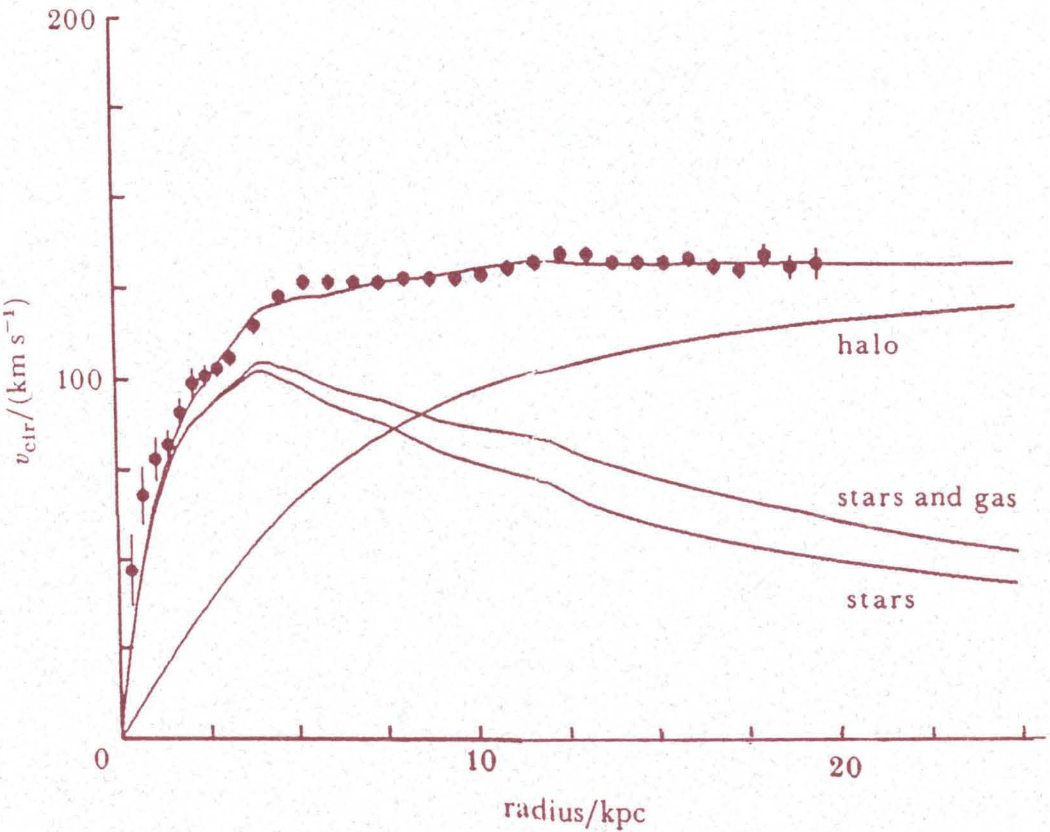

Figure 9 - An example of the contribution of the Luminous Matter (stars and gas) to the experimental determination of the rotation curve for galaxy NGC 2403. The curves are theoretical calculations. With increasing distances, the dominant contribution becomes that of dark matter (halo).

The gravitational constant G is a universal constant. It is amusing that although the first estimate of G was made earlier than that of almost any other physical constant (perhaps with the exception of the speed of light), its present determination is still much less accurate than that of most other physical constants. Figure 10 shows how much faster the precision in the measurement of the speed of light has progressed compared with that of G. However, the present knowledge of G is more than adequate for our purposes. H_o, in fact, is much less well determined. We can write it as

$$H_o = h \times 100 kms^{-1} Mpc^{-1},$$

where Mpc stands for *Megaparsec*, i.e. one million parsecs. In the above equation, *h* conceals our poor knowledge of H.[6] It is of order unity; its value being restricted by observation to lie between $0.4<h<1$.

The parameter normally used, however, is not the density itself but, rather, the ratio

$$\Omega = \rho / \rho_c$$

According to previous definitions, Ω smaller, equal or larger than unity implies open, flat or closed universe respectively. This is precisely why it is so important for our understanding of the universe to establish the experimental value of Ω.

There are several ways in which the value of Ω can be estimated,[7] but, as one may easily imagine, it is not an easy task to *weigh* the universe. As a consequence, a large degree of uncertainty affects the estimates of the density of *matter*. But we have a more difficult task: not only do we want to know how much matter there is in the universe, but we want to know what kind of matter it is. To get clues to the latter question, we need to turn to the world of the very small—the world of particle physics.

Just as cosmologists have a standard Big-Bang model of the universe, physicists have *a standard model of elementary particles*. This model is only about 20 years old, having been developed in the 1960's and 1970's. According to the standard model, the elementary particles of matter are *quarks* and *leptons*. These particles come in three *families*, and ordinary matter is made only of particles of the first family.

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[6]It is amusing that the same symbol *h* is used to give the uncertainty in our knowledge of the *Hubble* constant, which describes the expansion of the universe, and for *Planck's* constant, which describes the uncertainty connected with the microscopic world. The two uncertainties, however, are not interrelated.

[7]Included among the so-called kinematic methods are the luminosity red-shift, the angular size red shift, the number-count redshift, and the primordial nucleosynthesis.

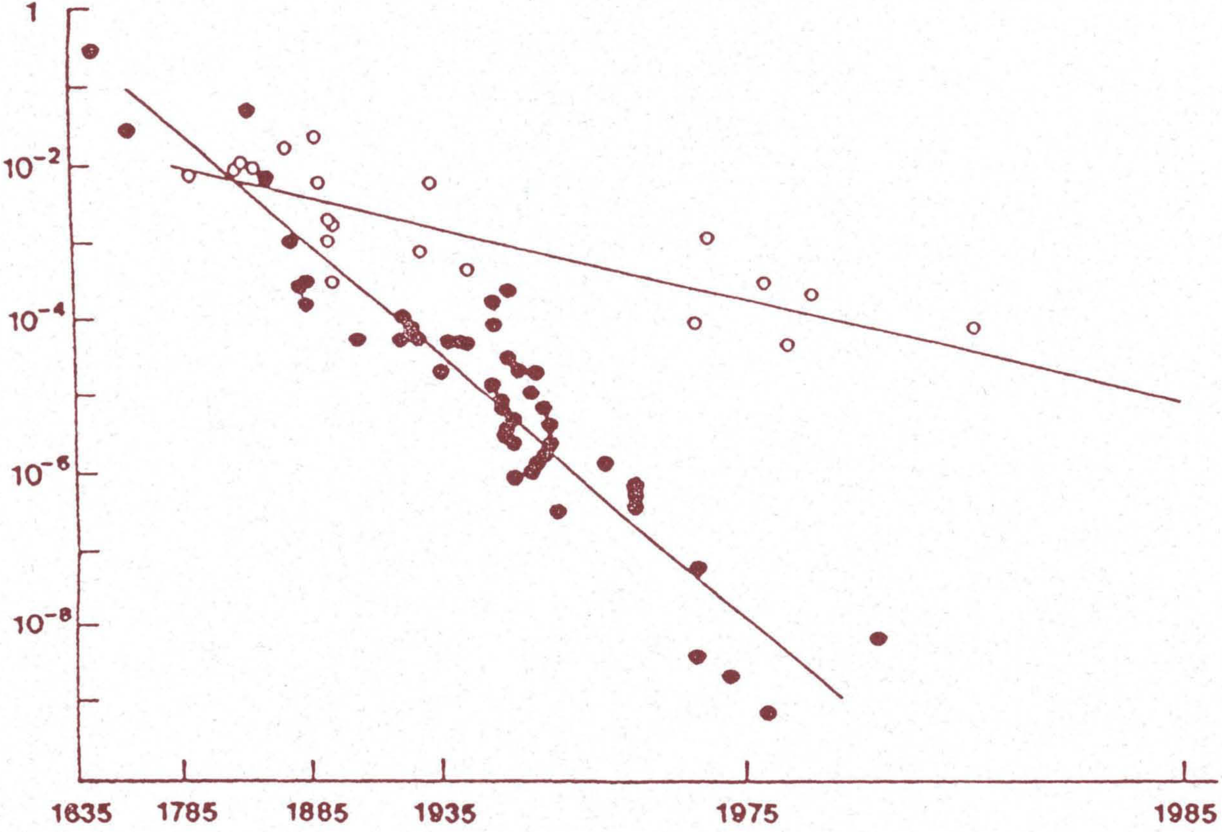

Figure 10 - The increase in fractional precision of Newton's gravitational constant G (open dots) and of the speed of light c (black dots). The value of the latter was fixed, by definition, in 1983.

The forces on the quarks and leptons are carried by quanta of *fields*, which exist in so-called "empty" space. *Photons* are quanta of the electromagnetic field, which is responsible for electric and magnetic forces. Particles called *gluons* are quanta of the *strong* or subnuclear force, which is responsible for confining quarks into protons, neutrons, and atomic nuclei. Finally, there are *weak bosons*, which are quanta of the *weak* force responsible for certain kinds of radioactivity.

We now return to the three families, each of which contains two quarks and two leptons. The quarks and leptons have picturesque names which have nothing to do with their physical properties. The quarks of the first family are called *up* and *down*. The leptons of the first family are called the *electron* and *electron-neutrino*. Up and down quarks combine into heavy particles called *baryons*, the two most familiar being the proton and neutron. Protons and neutrons in turn combine into atomic nuclei. These nuclei carry positive electric charge, and are often bound to negatively-charged electrons to form neutral atoms.

Particles of the second and third families, except for the neutrinos, have much greater masses than those of the first family, and lead fleeting existences, rapidly decaying radioactively into particles of the first family. However, we believe that particles of the second and third families played an essential role in the development of the early universe, and may play important roles even today in cataclysmic cosmic explosions like supernovae. Particles of the second and third families are presently a very fruitful area of study.

Neutrinos do not exist in atoms, but are created in radioactive processes and escape into the universe. A neutrino has a far smaller mass than the electron. For simplicity, the present version of the standard model assumes that all three kinds of neutrinos (one for each family) have zero mass.

Particle physicists commonly use an energy unit, the *electron volt*, abbreviated eV, to describe the mass of a particle. This can be done because of the equivalence of mass and energy, according to *Einstein's* theory of relativity. The electron has a mass of 0.511 MeV (million electron volts), while the proton (which is the lightest baryon) has a mass almost 2000 times as great (938 MeV). From these numbers it follows that almost all the mass of an atom is concentrated in its nucleus which is composed of baryons.

For cosmological purposes, the mass of electrons can safely be neglected compared to the mass of the baryons in the universe. That is why we give the name "baryonic matter" to ordinary matter. Baryonic matter, if at a high enough temperature, will *shine* by emitting light in the form of photons; much of this baryonic matter is the luminous matter concentrated in the stars. However, some baryonic matter is at too low a temperature to shine. Some of it is in the form of clouds of dust, either in or between galaxies; some of it is in burned-out stars; and some of it is very likely in planets of other stars. This kind of baryonic matter is part of the dark matter of the universe. However, it is probably not the only dark matter that exists, and is possibly only a small fraction of the dark matter in the universe. The exact amount and nature of the nonbaryonic dark matter is unknown at the present time. It is essential to learn about nonbaryonic dark matter in order to understand the past and future development of the universe.

First, let us consider the contribution to the mass of the universe from photons and neutrinos. The contribution of photons is known with relatively high precision: $\Omega_\gamma = 2.5h^{-2}10^{-4}$ where we have used the measured value $T_\gamma = 2.73$ K for the background radiation. The contribution of neutrinos depends critically on their masses. If neutrinos are massless, as is assumed in the standard model for simplicity, their contribution is $\Omega_\gamma = 1.7h^{-2}10^{-4}$. However, there is some experimental evidence that neutrinos may have small masses, and, if so, this estimate would have to be increased. If neutrinos are massless, the contribution of photons and neutrinos together to Ω is at most around 0.2%, and is only a small fraction of the mass of the universe. Depending on the masses of neutrinos, this estimate could change drastically. Neutrinos with masses in the right range could even close the universe. Thus, future experiments to obtain information about neutrino masses are crucial to our understanding of the universe.

We do not know the amount of baryonic matter in the universe with much accuracy. However, from our knowledge of the forces among particles, we do know that the amount of baryonic matter is far too small to close the universe. The evidence comes from primordial nucleosynthesis, i.e. from the estimate of the distribution of the light elements produced shortly after the *Big Bang*.[8] Input about forces among particles is essential to this estimate. Within a factor of 2 in uncertainty, the contribution to Ω from baryonic matter is $\Omega_B = (0.01 - 0.1)$. We know that Ω_B cannot be of order unity, or the abundance of deuterium (heavy hydrogen) would be severely underestimated compared to observation, while the elements ^{4}He and ^{7}Li would be overproduced.

One can estimate the density due to *luminous* matter in a galaxy such as *Andromeda*. From the measured rotational velocity and from simple physical

[8]Nothing of much interest has happened since, according to the American Nobel laureate *Steven Weinberg*.

laws, one finds that the fraction of critical density associated with luminous matter is very small, smaller than $\Omega_{lum} \approx 0.01$. Differently stated, the mass associated with luminous matter does not provide more than about 1% of the critical density.

Given our present understanding of elementary particle physics, if one puts together all kinds of astronomical observations, one reaches the conclusion that the total amount of ordinary baryonic matter, consisting primarily of protons and neutrons may exceed the observed luminous matter, but cannot account for more than ≈ 20% of the mass required for closure, i.e. $\Omega < 0.2$.

Before we proceed further, it is useful to summarize the situation as observed experimentally:

i) Luminous matter (in the form of stars and the like) provides at most 1% of the critical density.

ii) The flat rotational curves of spiral galaxies (Figure 9) and all other observations indicate that the largest contribution to the mass of the universe comes from dark matter.

iii) The density of ordinary matter of the universe (relative to the critical density) is estimated to be not less than $\Omega \approx 0.1$ and not more than ≈ 0.2.

iv) Dark matter is presumably less condensed than luminous matter since it seems not to be confined to galaxies. However, some candidates for dark matter, known as MACHOs, for *Massive Compact Halo Objects*, might be confined to regions around galaxies.

Let us now discuss the reason why we have emphasized the *observed* value of the density of matter in the universe.[9] We have seen that all observations tell us that the density of baryonic matter is between one and two orders of magnitude smaller than the critical value. However, several theoretical arguments, based on i) dynamical models to explain the measured baryon density, ii) our present understanding of some special topics related to general relativity[10] iii) the smoothness of the cosmic background radiation in all parts of the sky and, iv) the so-called inflationary scenarios[11] suggest that *the universe should be flat*. If

[9]As we have made clear, theoretical considerations, as well as astronomical observations, are necessary to let us estimate the density.

[10]The issue is the actual numerical value of *Einstein's cosmological constant*.

[11]As the term suggests, in order to explain why the universe has the size it has today, schemes have been devised leading to a faster growth of the size of the universe than would otherwise have been possible with the conventional schemes used earlier.

these arguments are correct, then, the implication is that if we could indeed measure *all* the matter in the universe, we would find $\Omega = 1$. Admittedly, and we have to insist very much on this point, *this is still a theoretical prejudice and not necessarily a fact*. But, if correct, this conclusion would imply that *the dominant constituent of the universe is dark matter*. As we have discussed, there is direct observational evidence that dark matter must exist. But here we are actually arriving at the conclusion that dark matter not only exists, but is the dominant component of the universe by at least an order of magnitude, and that, possibly, most of it is nonbaryonic!

The final question is then, what could this dark matter be made of, given that the *standard model* of particle physics has no natural candidates for it? As we have indicated, baryonic matter in the form of dust, burned-out stars,neutron stars, or very low mass stars cannot presumably provide the answer because the amount of baryonic matter is limited by the observed relative abundance of the elements. Furthermore, dark matter cannot consist primarily of black holes, since we have reason to believe that most black holes were formed from the collapse of baryonic matter. Halos of matter around the galaxies (MACHOs, see above), however, cannot be ruled out as dark matter, and such a possibility has been advocated by many astrophysicists. There could be stars whose thermonuclear reactions would be too weak to be visible, stellar-like objects that lack the mass to become nuclear-fired stars or planet-sized bodies much like Jupiter. But, because of the observed relative abundance of the elements, if the universe is flat, most of the dark matter causing the flatness should be different from the particles of the conventional standard model with zero-mass neutrinos. Thus, if MACHOs are made of conventional baryonic matter, they cannot be sufficiently abundant to cause the universe to be flat.

Particle physics rises to the occasion with speculations which go beyond the standard model. Entire families of new potential candidates have been proposed. Here, we will just enumerate the most promising ones.

The simplest among the possible candidates for dark matter are massive neutrinos, i.e. neutrinos with mass in the 10eV - 100eV range, i.e. between 50,000 and 5,000 times lighter than the electron. As we have seen, if neutrinos are massless, as postulated within the standard model, their contribution to Ω is negligible. The present experimental limits on the masses of the three neutrino species (which are called (ν_e, ν_μ, and ν_τ) are

$$m_e < 7.3\text{eV},$$
$$m_\mu < 270\text{keV},$$
$$m_\tau < 35\text{MeV}.$$

The above values show that massive neutrinos are serious contenders for the role of dark matter candidates, but a model-dependent construction of a neutrino dominated universe has proven difficult.

A somewhat more exotic but still possible candidate is a proposed very light particle called the axion,[12] with a mass in the range 10^{-4} - 10^{-6} eV.

A third, still more exotic, candidate for dark matter is called the *neutralino* and belongs to a family of the so-called *supersymmetric particles* postulated by some theorists to exist. In most supersymmetric models the neutralino is the lightest of all the new proposed particles and is stable against radioactive decay. Its mass, to do the job for which it is wanted in cosmology, ought to be in the 10 GeV - 2 TeV range (a GeV is one billion eV; a TeV is one trillion eV); i.e. from 10 to 2000 times as heavy as the proton.

Cosmologists have to be highly imaginative—some would use stronger terms—to suggest that particles like axions or neutralinos, which *we don't even know exist at all*, are what most of the universe is made of. If it were not for the fact that these proposed particles are supposed to have properties which make them detectable by experiment, these speculations would have no greater scientific content than the philosophical ideas of the ancient Greeks.

The hunt for dark matter is presently being very actively pursued; all the evidence is that dark matter exists, and many physicists believe that it can be observed. In the process, which may be long and laborious, new phenomena and new physics are probably going to be discovered, studied and clarified. Even though it is very unlikely that we will ever find the *ultimate truth*, that is no excuse for not looking for it.[13] The study of the universe is certainly the oldest

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[12]Axions emerge naturally in a scheme beyond the standard model of particle physics which solves theoretically a longstanding problem of particle physics known as the strong CP problem.

[13]At the time of this writing, the media reports the news that two teams, one American-Australian and one French, at a Workshop held at the Gran Sasso Laboratory (in Italy), have supplied evidence for the possible discovery of dark matter. The candidates are called MACHOs for *Massive Compact Halo Objects*. Their detection results from a gravitational effect called *microlensing*. The event in question, spotted while the groups were monitoring 3.3. millions stars, occurred in January 1993 in the *Large Magellan Clouds* (on the fringes of the *Milky Way galaxy*) as a star grew brighter. By the end of March it had returned to its normal brightness. The mass associated with this potential MACHO event is estimated anywhere between 3 and 30% of the mass of the *Sun*. The greatest care has been taken in reporting the observation that dark matter is only one of the possible interpretations and that much better evidence has to be gathered before any definite conclusions can be drawn.

one in mankind's search for truth, and to it we can no doubt apply what *Dante* put in *Ulysses's* mouth when the latter exhorts his companions not to get discouraged:

> . . . Nati non foste per viver come bruti
> ma per seguir virtute e caunoscenza.
> (Dante, La Divina Commedia, Inferno XXVI, 118)
>
> . . . You were born not to live like mindless brutes
> but to follow paths of excellence and knowledge.
> (Translation by Mark Musa, Penguin Classics (1984))[14]

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