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Excerpt
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1 Building blocks of the cosmos

Throughout the ages, cosmologists have imposed their world views on the fundamental nature of the universe. Modern astronomers have proved no exception. As the extragalactic universe began to be explored in the twentieth century, cosmologists felt impelled to incorporate their concepts of how the universe should be. In 1931, Ernest Barnes, a mathematician and theologian who was also the Anglican Bishop of Birmingham, asserted, among other things, that an infinite universe was abhorrent to nature. Many years later, physicist John Archibald Wheeler, father of the black hole, echoed this sentiment in arguing for a finite universe. Others, beginning with Albert Einstein, adopted the Platonic ideal that the universe should have no centre and should be perfectly isotropic, with no preferred direction. Only recently have we been able to test these assumptions, as some of the most fundamental issues in cosmology have been reassessed in the light of modern astronomical data. Einstein was right.

1.1 Cosmological principles

It is inevitable that an astronomer studies objects remote in time as well as in space. Light travels a distance of 300 000 kilometres in one second, or ten thousand billion kilometres in a year. The nearest star, Proxima Centauri, is 4.2 light-years from us, so we see it as it was about four years ago. The nearest galaxy comparable to our own Milky Way, the Andromeda galaxy, is two million light-years distant. We are seeing that galaxy, which is visible in a dark sky to the naked eye, as it was when *Homo sapiens* had not yet evolved. A large telescope is a time machine that can take us part way to creation. With a modern telescope, we can examine regions from which light emanated more than five billion years ago, before our Sun had ever formed. To a cosmologist, the issue of creation is inevitable.

There are three possibilities that one may envisage for the creation of the universe.

1. The beginning was a singular state, not describable by physical science. A sceptic might ask, what did God do before He created the universe? The apocryphal answer is that He was preparing Hell for people who might ask such questions (attributed to St Augustine).
2. The beginning was the most simple and permanent state imaginable, containing within itself the seeds of future evolution. This is the modern view.
3. There was no creation, and the universe is unchanging and of infinite age.

We can try to distinguish between the latter two possibilities, the only two options on which scientific tools can be brought to bear. To test this approach to cosmology, one searches for the correct physical laws that describe the initial state of the universe.

The scientist commences his study of the universe by assuming that the laws of physics that are locally measured in the laboratory apply more generally throughout the cosmos. In this spirit, cosmology, the science of studies of the universe, is developed by extrapolating locally verified laws of physics to remote locations in space and time. Objects and events at these locations can be probed with modern astronomical techniques. If these probes were to prove that we are wrong to assume that the physics we learn in high school is universally applicable, the scientist then would proceed to explore a more complex physics that may reduce to generalisations of local physics. In a theory of the universe, simplicity is sought on sufficiently large scales. The successful theories in physics and mathematics are invariably the simplest, with the least number of arbitrary degrees of freedom. Postulating that Atlas held up the heavens (where did he come from? why didn't he get bored? or sleepy?) requires many more ad hoc assumptions than the modern view of the celestial sphere. This is of course the view that the orbits of the planets in the gravity field of the Sun suffice to stop them falling onto the Earth like so many shooting stars.

Such considerations about the simplicity of a successful theory are incorporated into a simple principle that serves as a guide for building a model of the universe. This cosmological principle states that the universe, on the average, looks the same from any point; that is to say, it is isotropic. The principle is motivated by the Copernican argument that the Earth is not in a central, preferred position. If the universe is locally isotropic, as viewed from any point, it must also be uniform in space. So the cosmological principle states that the universe is approximately isotropic and homogeneous, as viewed by any observer at rest. This is the weakest version of the principle, but there are several others. This particular version of the cosmological principle is the foundation stone of modern cosmology. Modern observations have provided confirming evidence, as will be described in later chapters.

A stronger version, the perfect cosmological principle, goes further: the universe appears the same from all points and at all times. In other words, there can have been no evolution: the universe must always have been in the same state, at least as averaged over long times. In this sense, the perfect cosmological principle contrasts with the weaker version, which allows the possibility of very different past and future states of the universe. The perfect cosmological principle spawned the theory of the steady state universe described later.

Unlike other branches of science, cosmology is unique in that there is only one universe available for study. We cannot tweak one parameter, juggle another, and end up with a different system on which to experiment. We can never know how unique is our universe, for we have no other universe with which to compare it. The universe denotes everything that is or ever will be observable, so we can never hope to glimpse another universe.

Nevertheless, we can imagine other possible universes. One could have a universe containing no galaxies, no stars, and no planets.

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Needless to say, man could not exist in such a universe. The very fact that our species has evolved on the planet Earth sets significant constraints on the possible ways our universe has evolved. Indeed, some cosmologists think that such an anthropomorphic approach may be the only way we can ever tackle such questions as, why does space have three dimensions, or why does the proton have a mass that is much larger (precisely 1836 times larger) than the electron, or why is the neutron just 0.14 per cent heavier than the proton? If any one of these were not the case, we certainly would not be here.

One can take the argument further. Our actual existence requires the universe to have had three space dimensions and the proton mass to be 1836 electron masses. Our bodily processes would be a malfunctioning mess in a universe of one or two space dimensions. This conclusion that the universe we inhabit must have certain properties essential for our existence is called the anthropic cosmological principle: namely, that the universe must be congenial to the origin and development of intelligent life. Of course, it is not an explanation, and the anthropic principle is devoid of any physical significance. Rather it limits the possibilities. There could be a host of radically different universes that we need not worry about.

The anthropic cosmological principle argues that the universe must have been constructed so as to have led to the development of intelligence. This version of the cosmological principle begs the question of how likely is the development of life, and indeed the observable universe, from suitably random initial conditions. At least in principle, this is an issue resolvable by physics rather than by fiat. Inflationary cosmology, described in Chapter 5, purports to do just this.

Cosmology comprises the vast and the infinitesimal. In measuring the ingredients of the astronomical universe, astronomers deal with a range of magnitudes that stretches the limits of human conception. I begin with a look at this range of magnitudes to set the scene for the cosmological drama that will subsequently unfold.

1.2 ORDERS OF MAGNITUDE

Astronomers have a language of their own, that at times make it difficult for those outside the field. This language involves specific terms: who but an astronomer would ever utilise a parsec (pc), a distance of 3.26 light-years, to measure the unit of distance? In addition, the language of astronomy takes a heuristic approach to numbers. It is enough in many instances to specify a number to two or even one significant figure. Factors of 10 are called 'orders of magnitude': it is important to have the correct order of magnitude, but often that suffices.

There is a proliferation of factors of 10 that is endemic to astronomy. We know that the mass of the Sun is 2×10^{33} g, a large number even in megatonnes (2×10^{21}). Such large exponents may seem meaningless, but, if one errs by an order of magnitude, the star is a dwarf or a giant, and very different in its observable properties. To reduce the size of the exponent, it is common to use the mass of the Sun ($M_\odot$) as the unit of mass in astronomy. Our Milky Way galaxy weighs in at about 100 billion, or 10^{11}, ($M_\odot$), in terms of the visible matter. We may be off by 10 billion $M_\odot$, in either direction, but we have to settle for an accuracy of 10 per cent. Rounding off to one, sometimes two, significant figures is normal in astronomy.

Of course there are examples where astronomical data are of exquisite accuracy. Our universe is bathed in a cold sea of microwave radiation; the temperature of this cosmic background radiation is measured to be 2.726 kelvin (K), or −270.42 degrees Celsius (°C). But specifying it as 3 K usually is adequate. The problem invariably encountered is that the remote stars and galaxies yield so few photons for our detectors that we indeed have the sparsest information in most cases. Astronomers are data starved, despite the flood of data from new telescopes and satellite experiments, simply because the objects being studied are generally so dim.

The range of orders of magnitude needed to describe the physical universe is huge. For example, how large a number can one imagine as having any physical significance? Let us consider the number of atoms in the observable universe, as a simple illustration of orders of magnitude. One gram of hydrogen, the predominant form of matter, contains about 10^{24} atoms (in order of magnitude). Hence the Sun, with a mass of 2×10^{33} g, contains 10^{57} atoms (in order of magnitude), and the Milky Way, containing some 100 billion suns, about 10^{68} atoms (in order of magnitude). On a truly dark night, the observer can see with the naked eye one galaxy, Andromeda, which is the counterpart in stellar content to our own Milky Way. With the aid of the largest telescopes, the sky is found to be teeming with galaxies. As many as 200 000 per square degree can be counted. For comparison, the Sun covers about one-quarter of a square degree. The entire sky contains 41 000 square degrees. There are consequently nearly 10 billion galaxies in the observable universe, or about 10^{78} atoms (in order of magnitude). This is the largest meaningful number in the universe.

To find the smallest number in the universe, we look for the smallest object. An atom has a size of the order of one-hundred-millionth of a centimetre, yet is far from being the smallest object in the universe. The nucleus of a hydrogen atom is about 10^{-13} cm across. But the single proton forming the hydrogen nucleus is known to be composite, to consist of smaller entities called quarks. Truly fundamental particles are point like; for example, both electrons and quarks have point-like interactions. A point-like particle has no measurable diameter; instead, a measure of the effective dimension of such a particle is given by the uncertainty that quantum theory assigns to its position. One can never pinpoint with complete precision the location of a particle. The greater the mass of a particle, the smaller is the quantum uncertainty in location, a measure of length that is called the Compton wavelength. The smallest Compton wavelength is for the most massive particle that is permitted by theory to exist without collapsing to a black hole. Such a particle has a mass of 10^{19} proton masses, and has a Compton wavelength corresponding to a dimension of about 10^{-32} cm. This, one can claim, is the smallest length scale that can exist (if such particles exist) in the universe.

1.3 BUILDING BLOCKS OF THE UNIVERSE

The universe beloved of astronomers consists primarily of stars and galaxies. These luminous objects provide a measure of the universe, and are the key to unlocking its secrets. For example, it is the brightest stars that can be seen from afar as cosmic beacons, and that are vital to the reckoning of extragalactic distances. Also important are the dark clouds of gas and dust, whose measurement is a clue to the amount of matter in the universe and to the mysteries of star formation. It is impossible to understand how cosmologists study the universe without knowing something about these objects.

1.3.1 Clouds in space

A star begins life as an interstellar cloud of gas and dust. The interstellar gas consists of cold clouds of a variety of sizes embedded in a more uniform, warmer gas layer that pervades our galaxy. The clouds range in size from a parsec to a hundred parsecs, and contain between a few solar masses and a few million solar masses of gas. The denser clouds are predominantly dark clouds of *molecular* hydrogen, the more diffuse clouds are *atomic* hydrogen. A third form of hydrogen, *ionised* hydrogen, surrounds massive stars, and is in brightly glowing nebulae.

Spectroscopy is one of the astronomer's most important tools for studying gas clouds, and the universe in general. Every atom has its characteristic spectral signature: it absorbs or emits radiation at a specific series of wavelengths. An instrument called a spectrograph enables astronomers to obtain the spectral signatures of the atoms inside a gas cloud. This instrument breaks light down into its constituent wavelengths, to give a spectrum. Excited atoms in the cloud returning to their unexcited states emit radiation that shows up in the spectrum as bright 'emission lines' at the signature wavelengths.

Emission lines are only visible when a cloud is viewed in the absence of a bright background light source. Alternatively, if a gas cloud is observed against a background of hotter radiation from some other source, its atoms will absorb the background radiation at their characteristic wavelengths, creating gaps or 'absorption lines' in the spectrum of the radiation. Stellar spectra, produced by the atmospheres of stars silhouetted against the opaque hot stellar cores, have unlocked the secrets of the stars, and their detailed composition has been inferred. Spectral lines are broadened as a result of the random motions of the atoms in the hot atmosphere of a star, and so stellar absorption lines are characteristically broad.

Interstellar clouds were discovered about 60 years ago, when narrow absorption lines were first detected in stellar spectra. The stars being studied were occasionally variable or binary stars, with spectra whose absorption lines should have disappeared as the star dimmed or became hidden behind its binary partner, yet the absorption lines, much narrower than the usual stellar lines, were unchanging in strength or wavelength. Their narrow width showed that they originated in a cold gas, at a temperature of less than 100 K, much colder than typical stellar temperatures of at least a few thousand degrees. The traditional spectrographs could only analyse visible light, so the lines seen were produced by sodium, calcium, and a few other relatively rare elements that have spectral lines in the visible part of the spectrum. These elements were soon identified as being trace constituents in clouds of atomic hydrogen.

The atomic hydrogen in these clouds was discovered in the 1950s, with the development of radio astronomy. An atom of hydrogen may be visualised as containing two tiny magnets, associated with the electron and the proton. The magnets may be either pointing in opposite directions or aligned in the same direction. These two states have slightly different energies, and a transition from one state to the other results in the emission or absorption of a photon with a wavelength of 21 cm, in the radio portion of the spectrum. Despite the very low probability of such a transition occurring (it takes about 10 million years for the magnet to flip), the immense numbers of atoms in an interstellar cloud generate enough photons to be observable with radio telescopes. With the advent of instruments able to analyse the ultraviolet spectrum, in the 1960s, the abundant heavy elements, such as carbon, nitrogen, and oxygen were also discovered in interstellar clouds.

Our galaxy contains about two billion solar masses in the form of atomic hydrogen (HI), in clouds typically of diameter 10 pc, temperature 100 K, and density only about 10 atoms per cubic centimetre. The principal absorption line produced by atomic hydrogen is in the far ultraviolet spectral region at 1216 angstroms (Å), where 1 angstrom is 10^{-8} of a centimetre. Called the Lyman alpha absorption line, it was only detected when the first rocket-borne telescopes were lofted high enough above the atmosphere to detect far ultraviolet radiation from space, after ultraviolet astronomy was developed. Since the atomic clouds were known to contain dust, it was conjectured that the dust in a sufficiently dense cloud would shield the cloud centre from ultraviolet light. Light at these energetic wavelengths breaks molecular bonds; when shielded from its effects, two hydrogen atoms are able to join to create molecular hydrogen (H_2). Thus, molecular hydrogen should be the dominant form of hydrogen in a dense cloud. This conjecture was confirmed with the first detections of hydrogen molecules by the recording of their ultraviolet absorption lines. Because of the pervasive interstellar dust, ultraviolet astronomy is a nearly useless technique for penetrating into dense interstellar gas clouds.

Most interstellar molecules are in fact detectable not in the ultraviolet but at microwave frequencies. Clouds of molecular hydrogen, despite the chill of interstellar space, are warm enough, at a few tens of K, to excite common molecules such as water and ammonia into higher levels of rotational energy, levels for rotation of compact molecules, similar to energy levels seen in atoms, but with much less energy. After being excited to higher energy levels, these molecules emit at microwave frequencies as they return to the lowest energy state. These low-energy rotational transitions lead to photons of much lower frequency (at radio and microwave frequencies) than the photons produced by electronic transitions in atoms (typically visible and ultraviolet). It required the development of *microwave* astronomy in the 1970s before the densest interstellar clouds were studied and shown to contain an extraordinary variety of molecular species.

Astronomers searching for the spectral lines at microwave frequencies have discovered hundreds of different molecules, including methyl alcohol, ammonia, water, formaldehyde, and some relatively complex molecules. The most common molecule, after H_2, is carbon monoxide, which has a strong spectral line at a wavelength of 3 mm. Only at densities above 100 atoms per cubic centimetre is molecular hydrogen the dominant form of hydrogen. For molecules to predominate, the clouds must be exceptionally dark, and shielded by dust from the diffuse interstellar radiation field of starlight. In these molecular clouds, typical hydrogen densities are 1000 atoms per cubic centimetre and typical temperatures are about 30 K. There is at least as much interstellar gas in molecular form as in the atomic phase in our galaxy.

Although the temperatures are low, the thermal energy of the atoms supplies enough kinetic energy to keep a cloud's atoms in a state of continuous jostling. These thermal motions exert a pressure force that tends to make the cloud expand, and thereby counter the opposing tendency of the cloud's own gravity. The life of an interstellar cloud is a continuous struggle between the sustaining force exerted by thermal pressure against the relentless grip of gravity that drives the cloud toward collapse. As clouds orbit the galaxy, they accrete mass. They also radiate and cool. Gravity eventually wins the battle. Once thermal energy cannot withstand the force of gravity, clouds begin to undergo gravitational contraction. Gravitational collapse soon ensues, and eventually the cloud becomes so dense and opaque to molecular radiation that its core heats up. A gravity-powered *protostar* forms, or, most likely, a cluster of protostars. The protostar phase of the Sun demarcated the formation of the Solar System. Gravity power, however, has a finite duration. The protostar phase is long (more than 30 million years) for stars of mass less than the Sun, but relatively short for the most massive stars.