Big Bang Cosmology: A Model Of A Dynamic, Evolving Universe

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Abstract

This essay deals in an abbreviated way with the contemporary view of the origin, structure and evolution of the universe, based on the standard cosmological model called the Big Bang. In this model the universe is dynamic and changing, and has expanded and evolved from an early extremely hot and dense state to its present state over a period of 15 to 20 billion;years. The underlying assumptions and the observational evidence for the validity of this model are reviewed. Some questions about the role of *homo sapiens* and the existence of an extramundane entity are addressed in an epilogue.

Introduction

A full description of the Big Bang model is a textbook endeavor, coupled with the need for the reader to have a background in mathematics and modern physics. In this essay an attempt is made to sketch the details of the model for a lay audience; some intellectual stretch is required of the reader in any case, since some of the concepts embedded in the model are counterintuitive, as is the case for so much of contemporary physics. It is hoped that the reader will find the effort worthwhile and will be left with enough insights to appreciate the excitement of new discoveries about the universe being announced almost weekly in the media.

The plan for this essay is to first sketch the definitions and assumptions that underlie the model. The observational evidence for the model is then reviewed. The essay continues with a description of the model, including remarks about the formation of structures in the universe, which is almost a subject by itself. Then a view is given of the very early universe, whose characteristics are particularly difficult to comprehend but which is an active area of current research. Finally there will be a bit of speculation about the future of the cosmos. Some remarks are scattered through the text about the history of the subject, and a short reading list is provided for those who are intrigued by the ideas and the history of the subject, and want to learn more about them. In an epilogue, I address very briefly, some of the "theological" concerns which are raised from time to time in discussions of cosmology.

By way of an apology, I would remark that the language of physical science is mathematics, and that it is at least challenging for scientists to attempt to convey the content of a model of the universe without mathematics.

DEFINITIONS AND ASSUMPTIONS

Cosmology is that branch of physical science which deals with the origin, structure and evolution of the universe, defined to be the observable ensemble of atoms, molecules, planetary bodies, radiation of all wavelengths (from gamma rays and x-rays through the visible light spectrum, to the infrared and on into radiofrequencies), neutrinos (very light or massless exotic elementary particles which are important in astrophysics and cosmology), gas, dust, stars, galaxies of stars and clusters of galaxies. Much of the gas is in a plasma state, i.e. it consists of positively charged ions, i.e., atomic nuclei stripped of electrons, and free negatively charged electrons, with the sum of positive and negative charges being zero.

Some assumptions are essential in making progress toward an understanding of the universe. You may find the assumptions to be oversimplified, but scientists generally find it good practice in developing a theory to keep their assumptions as simple as is consistent with the development of a useful and successful model. It is only as a last resort that scientists invent new phenomena in order to bring a model into closer agreement with observation.

Cosmologists assume that the fraction of the universe we see is a fair sample. According to essentially all proposed models of the universe, astronomers now observe only a fraction of what we shall ever be physically able to observe. We really do not know how big this fraction is. There are current observations of objects whose distance is estimated as being perhaps as much as a half of the radius of the potentially visible universe. Since the volume of a sphere varies as the cube of the radius, this means we are seeing about 10 to 15 percent of the volume of the potentially visible universe. If somehow we determine that this fraction is not representative, then the task of modeling the universe would be more complex. This is not a trivial assumption, for in the recent past astronomers have found such large scale structures in the universe as to stretch the validity of the "fair sample" assumption.

Perhaps the most important assumption made in cosmology is that the universe is understandable. This is an implicit assumption. If one finds the universe to be indifferent to human existence, chaotic, and operating in a probabilistic way, it is nevertheless thought not to be "capricious." It is not playing games with us, a point strongly emphasized by Albert Einstein. On the other hand, nowhere is it written that understanding the universe will be a simple matter.

The well-tested Einstein theory of special relativity provides cosmologists with the ability to travel back in time. The theory of special relativity postulates that the velocity of light is both finite and constant, namely, about 186,000 miles per second. Moreover, there is a counterintuitive aspect of the propagation of light, namely, that this velocity is independent of the velocity of the light source or of the observer. So far as we know, the fastest possible way to transmit information is at the velocity of light. For example, the Sun is at a distance from Earth of about 93 million miles. If the Sun were to suddenly snuff out, we would not know it until light reached us and this would take about eight minutes. It would take about four years for light to reach us from the star nearest the sun. If the universe is 17 billion years old and was somehow producing light from the beginning, then we can in principle observe at most only out to a distance of 17 billion light years (seventeen billion years times the velocity of light). It is the volume defined by this distance which in turn defines the potentially visible universe.

This observable horizon grows with the aging universe at the velocity of light. Thus, when the universe is a billion years older than it is now, we should be able in principle to see objects at a distance of 18 billion light years. To emphasize the significance of this remark about time travel, let it be noted that if we observe a celestial object at a distance of, say, 10 billion light years, then we see that object by light emitted 10 billion years ago, when it was much younger, closer to its neighbors, and probably a much less evolved entity.

The basis of the Big Bang model is that the universe was hotter and denser in the past, and that the universe and all the objects in it have evolved from that earlier state. Thus, it is an important aspect of cosmological research to try to understand how the light output of galaxies changes as the stars are born, live and die within the galaxy whose collective light output we study. All stars have a finite lifetime, and their characteristics change as they age. To reiterate, special relativity provides us with a kind of "time travel" into the past.

Observation and special relativity indicate that the universe is homogeneous and isotropic, which leads to several alternatives for the geometry of the universe. It is generally accepted by cosmologists that the universe is the same everywhere on a large scale, and is the same in all directions. This defines the terms homogeneity and isotropy, respectively. The geometry of the universe consistent with these statements is one that is infinite in extent, or else is finite but unbounded. One way to think about infinite extent is to realize that if it were finite, then one would have to deal with the idea that there is something beyond. But this contradicts the concept of "universe" we are pursuing, where we take the meaning of the word universe as "all there is." The possibility of the universe being finite but. unbounded can be visualized by imagining that all of the objects in the universe are flattened and pasted to the surface of a sphere. A resident of this universe can move in any direction on the surface without limit, for there are no edges. Such a universe is clearly finite in size but has no boundaries. A resident of such a universe would have to do clever experiments to deduce that he lived on a spherical surface. (How do ~ know that the Earth's surface is curved?) However, an observer resident in a higher dimensionality might see the whole sphere at once.

In the language of relativity we deal with events rather than points of location in space. We can specify the *position* of an object by giving three numbers (the usual three dimensions), but an *event* associated with this object requires specification of a fourth number, the time. This fourth number is treated as a dimension, whence an event is defined. If the universe were a "four-dimensional sphere" (with three dimensions of space and one of time), then it could be viewed en toto from a higher dimensionality, namely, five. In general relativity and in the Big Bang model we speak of a four-dimensional space-time as the defining geometry. As will be described later, this space-time has additional geometrical properties which depend on the distribution of matter and energy in the universe and its rate of expansion.

Cosmologists refer to the homogeneity and isotropy of space as the "Cosmological Principle." If the cosmos is unchanging with time, a modality on which the now-defunct notion of a "steady state universe" is based, one refers to the "Perfect Cosmological Principle."

Homogeneity and isotropy on a large scale lead to the statement that all observers are assumed to be equivalent, wherever and whenever they may be. There are no privileged observers. To understand what is meant by a large or cosmological scale, we must expand our view and talk about galaxies, or even clusters of galaxies, as the fundamental building blocks of the cosmos. Consider that the universe is filled with galaxies, separated from one another by distances of the order of several millions of light years, and each of which is like our Milky Way in that each contains billions of stars. The Milky Way is an object whose visible constituents are made up of stars, gas and dust distributed in a disk through a volume of about 10,000 light years in thickness and 100,000 light years in breadth. This huge assembly rotates about an axis perpendicular to the plane of the disk once every quarter of a billion years. It may also contain a large amount of matter in a more-or-less spherical halo which we have been able to detect only by its gravitational influence. It has not yet been rendered visible by any existing technique. The Sun and its system of planets occupy an undistinguished position in the plane of the disk, about two-thirds of the way out from the axis of rotation. Were one to view the Milky Way from a considerable distance, one would find the stars, gas and dust concentrated into arms, which give the galaxy the appearance of a multiarmed spiral. Astronomers point out that the Andromeda Galaxy, which is at a distance of some two million light years, looks very much like the Milky Way.

There is another major type of galaxy, present in considerable numbers in the cosmos, called elliptical, which is comparable in extent to a spiral galaxy but which does not exhibit the arm structure of a spiral and contains little gas or dust. Whether they be spiral or elliptical, or of an intermediate form called "irregular", galaxies seldom occur alone, but, rather, are found in clusters with as many as a thousand or more members.

Thus, when we speak of large scales or cosmological scales, we are speaking of distances which encompass at least several clusters of galaxies, or several hundred million light years. Let us introduce the concept of an average density of the universe. By this we mean that if the total mass of matter plus radiation in a given volume of space were smeared out uniformly through the volume, then the average density is that total mass divided by that volume; put differently, the average density of matter is what would obtain if all the material collected in the clusters of galaxies were somehow redistributed as a uniform cloud throughout the space occupied by the clusters.

The laws of nature are universal. The laws which have been identified and studied by scientists in their laboratories or within the local Solar System are equally valid elsewhere and everywhere and at all times in the universe -valid at all scales of observation, from the basic constituents of matter to the majestic clusters of galaxies, from nearby in space and time to great distances and times in the past, representing significant fractions of the age of the universe. One should keep in mind that these laws are constructed by scientists to represent the observed properties of matter and energy. This assumption of the universal validity of the laws of nature may in some instances be tested by observation.

For example, the laws governing the emission of light by hot chemical elements in objects five billion light years distant have been compared with those governing the emission of light from the same elements in the laboratory. The laws, which are characteristic for every element, are the same.

In the end all that the scientific process can provide in understanding any physical phenomena is a theory and a model, coupled with observational data which make the theory and model credible. The "Big Bang" model is based on Einstein's theories of special and general relativity, and incorporates our contemporary understanding of the behavior of matter and energy. General relativity models gravitation, the major long-range force in the universe which controls the structure of the universe on astronomical scales, as well as locally preventing us from flying off into space. In addition, our understanding of nuclear physics and the physics of the elementary constituents of matter provides a basis for understanding the composition of the universe as well as details of its evolution.

The assumptions I have described appear to remove from consideration the possibility of a central position for *Homo Sapiens* in the cosmos. This means that any observer, wherever located in the universe, will see the same thing when viewing the sky on a large scale. The reader is invited to consider how little of the universe could possibly be in contact or have received information from us, i.e., how small a volume of space has been traversed by light carrying information about the existence of Homo Sapiens. Given that light is the information carrier, information corresponding to the epoch of Jesus is confined to a sphere of radius two thousand light years, which is merely a fraction of one percent of the volume of the Milky Way itself; man-made radio signals occupy a sphere of 70 light years radius, which contains perhaps a few hundred stars. By and large signals carrying the programs of Milton Berle, Ed Sullivan and other stars of our early forays into television broadcasting have not gotten very far on the cosmic scale, which may after all be a good thing.

I argue personally for the Big Bang model of the universe as a physical theory whose value lies in its predictive ability, in the way in which it encompasses simultaneously many and diverse astronomical observations, and, in particular, because it continues to survive the challenge of observational falsification. If it turns out to be wrong or inadequate as the result of observations yet to be made, I may be disappointed, but I will argue that science frequently progresses when existing ideas are proved wrong or inadequate and must be altered or replaced by new concepts. To put it simply, a basic attribute of good science is that it is self-correcting.

Scientific research involves the interaction of theory and experiment (observation in astronomy) and a theory or model of what is being studied. The model is not reality. For example, the Darwinian theory of evolution of living organisms provides a long-surviving and thoroughly tested framework for study and prediction. The theory is a scientific artifact, but it is surely not productive to criticize evolution in a highly pejorative sense as just a theory; theories are all we have. But theories and models change and evolve.

In any event the Big Bang model has not only survived over a number of decades, but the case for it has progressively become stronger. The turning point in the acceptance of the validity of the model by the scientific community was the discovery in 1965 of the cosmic microwave background radiation. In sum, the Big Bang model is alive and well, but it must be remembered that the theory and modeling are provisional activities representing an ongoing development of scientific understanding. The major difference between cosmology in the twentieth century and what was considered correct in the nineteenth century and earlier is the modern view that the cosmos is dynamic and has evolved from an early hot dense state. It is no longer correct to view the cosmos as static and unchanging from "everlasting to everlasting."

Evidence For The Big Bang Model

Indirect Evidence: The physical and astronomical evidence for the current Big Bang model of the universe is certainly convincing, but some evidence may be less direct than others. Indirect but significant evidence is the observation that on a large scale (many millions of light years in extent) the universe appears to be homogeneous and isotropic, concepts which I have already discussed. This, together with the uniformity of the composition of the universe, suggests a common origin for the major features. It is important that the theory of general relativity, which is the basis for modeling the large scale structure of the universe, argues against a static or unchanging universe and for a dynamic or evolving universe, one that expands, or expands and then contracts, or that goes through a series of expansions and contractions, i.e., oscillations, all of which are characterized as evolutionary.

Other phenomena suggest an evolving universe. Modern observational techniques enable one to estimate the age of the chemical elements from the present existence and relative amounts of radioactive nuclear species. Such species exist in nature, and undergo spontaneous change at a precisely measurable rate, from one variety of nucleus to another, usually through a sequence of steps culminating in a nucleus which is stable against further change. Knowing the radioactive decay rates, one can estimate. when the species were originally formed. That radioactive species exist at all suggests that they were formed at a finite time in the past, or are being created continually, both of which argue for an evolving universe.

The evolution of stars is also an indicator of cosmic age. Stars are formed from the condensation of gas and dust under the action of gravitational forces; when they become sufficiently condensed, heat and pressure at their cores will cause nuclei to react with one another, with the energy output being removed from the star as radiation and neutrinos. The heat and pressure maintain the star in a stable state, so long as there is a supply of nuclear fuel. There are good theoretical models of stars which enable one to calculate how long stars of a given type can survive before exhausting their nuclear fuel. These models indicate that some massive bright stars will live only millions of years, while smaller less luminous stars like our Sun may live quite uneventfully for billions of years. Study of the properties of stars gives us a view of the age distribution of stars, much as studies of a human population can give us a view of the average age and distribution of ages.

In addition, we can derive ages from the several types of clusters in the cosmos. There are clusters of stars within galaxies, as well as clusters of galaxies, which are bound together by their mutual gravitational forces. Given the proclivity of such collections to disperse because they are moving with respect to one another, it is possible to calculate how long a grouping recognizable as a cluster is capable of surviving.

Somewhat less obvious but nevertheless convincing to many is the evidence of astronomical radio sources and quasars. In the case of the sources of radio emission, of which there are many and which are undoubtedly galaxies, one uses a radio telescope to count the number of such objects which are radiating at given intensities. Putting the details of data analysis aside, one finds there are more such objects in a given volume of space at a greater distance; given the finite velocity of light we are seeing these greater number of objects in the past, suggesting that the separation of radio sources was less in the past, and that therefore the universe has evolved from a denser state. Another class of objects, called quasars, are thought to be very young and very luminous galaxies seen at great distances. Light characteristic of the element hydrogen can be seen in these objects, but the light is reddened as compared to similar emission from hydrogen in the laboratory, and this reddening signifies that these objects are receding. If this reddening is related to the expansion of space, then quasars are found to be among the most distant objects we can observe. Their existence and numbers, as with the radio sources, are consistent with the Big Bang model.

<u>More Direct Evidence:</u> There are at least three strong pieces of evidence which are regarded as pillars of the structure of the Big Bang model. First and most important are the famous observations by astronomers Hubble, Humason and Slipher at Mt. Wilson Observatory in the 1920s and 1930s. They found that on a large scale galaxies are seen to be receding from one another with a separation velocity proportional to their separation. Observers everywhere in the universe will see the same effect. The word "everywhere" is significant here, for it distinguishes the Big Bang from the simple but irrelevant model of a bomb exploding. Galaxies which are now further away had to have been traveling at a higher speed to arrive where they are now. Thus, one has the velocity-distance relation, known as Hubble's law, in which the apparent recession velocity of galaxies is proportional to their distance from the observer. In the seventy-odd years since this result was first published, no acceptable alternative physical explanation has been developed for the reddening (red shift or Doppler shift) on which the Hubble law is based. Again, I note that in terms of general relativity, what is actually expanding is the yardstick which one uses to measure distances. To reiterate why the simple exploding bomb analogy is inapplicable, note that

the cosmic expansion has an "origin" in time (it began at time zero) but has no preferred location in space (infinite or unbounded universe), consistent with there being no preferred observers. Cosmologists frequently try to clarify this by using a "raisin bread" analogy. Consider a mound of dough with raisins randomly dispersed within. Bake the dough so that it rises. Imagine yourself on one of the raisins. You will observe the other raisins moving away from you with velocities proportional to their distance from you. But so also would an observer on any other raisin. So long as the crust is sufficiently far away, all raisin-resident observers will be equivalent, and there will be no center from which the bread rises which can be identified by the raisin observer.

It is at least provocative that all cosmic age-determining techniques give an age of 15 to 20 billion years, consistent with the age one can derive for the Big Bang. In the Big Bang model, age can be calculated from a knowledge of two parameters, one being the rate of expansion of the measuring sticks of the universe, given by the Hubble parameter (the constant of proportionality between velocity and distance), and the other being the average density of matter in the universe. A simple calculation based on the incorrect bomb analogy just mentioned requires that one assumes the flight or recession of galaxies from one another to be not unlike the dispersion of fragments from an exploding bomb. If there is no retarding force on the fragments, then from measurements of the velocities one can calculate back in time and find the time of, the explosion. This result, applied to the cosmic expansion, yields the so-called Hubble age, a very crude determination of the age of the cosmos.

The second major piece of evidence has to do with the observed relative abundance in the universe of the light chemical elements helium and its isotopes, deuterium (heavy isotope of hydrogen), and, according to very recent studies, the element lithium. It is now clear that these elements, along with some beryllium and boron, collectively called the light elements, must have been synthesized during the early minutes after the Big Bang, when conditions prevailed not unlike those just after the explosion of a hydrogen bomb. We say "must" because it has not proved possible to model the production of cosmic relative amounts of these lightest elements inside stars, which is the only place other than the early universe where inferred physical conditions suggest that new nuclei can be formed. The first suggestion that the early hot dense state of an expanding universe was the site of formation of the elements was made in 1942 and 1946 by the late George Gamow. The mathematical basis for the model was derived from the work of Einstein by a number of people from 1917 to the 1940s, principally Alexander Friedmann in the USSR and Abbe Georges Lemaitre in Belgium. The earliest calculations of cosmic nucleosynthesis in such a model were carried out by the author with the late George Gamow in 1948, and improved and extended starting in 1948 by the author with Robert Herman. Herman (now at the University of Texas in Austin) and I are still collaborating on aspects of this work today. I would note that the descriptive words "Big Bang" were first used by British cosmologist Fred Hoyle in the heat of a radio debate with George Gamow about the relative merits of our work and the work of the now defunct "steady state or continuous creation theory." Like it or not, and despite a recent national contest to find another name, we are stuck with the name Big Bang.

It is now reasonably clear that the cosmic relative abundances of the other and heavier chemical elements, up through iron, are indeed established in stellar interiors by nuclear reactions starting with hydrogen and the other light elements already present in the stars as they formed from primordial material or material already cycled through earlier generations of stars. These reactions are driven by high temperatures and densities in the central cores of the stars, and the newly synthesized heavier elements are subsequently dispersed into interstellar space by violent explosions of evolving stars, called supernovae. In the process of explosion, elements heavier than iron are created on a very fast time scale. Much of the residual core material and the newly created elements become dispersed and then collected again in the formation of later generations of stars. The residual core becomes either a neutron star or a black hole, concepts which are beyond the scope of this essay. If a star is small to begin with, it may evolve without explosion into what is called a white dwarf. The various nuclear species dispersed from the stellar cores and subsequent explosions are collectively known as the heavy elements. The agreement between observed relative abundances of the light elements and those calculated from the Big Bang model in the process termed primeval nucleosynthesis, is surprisingly close, while the theoretical models of heavier element nucl eosynthesis in evolving stars and in their subsequent explosions are also in good agreement with observation. A recent supernova called SN1987 A occurred in a satellite galaxy called the Large Magellanic Cloud, at a distance of 170,000 light years, and was the subject of intense study with modern instrumentation. It verified much of the theory of supernovae explosions.

The third piece of evidence is what has been called, for convenience, the "three-degree radiation." It is now widely accepted that there exists electromagnetic radiation in the universe which can be characterized as the radiation from a 2.726 Kelvin (K) black body. In physics, a black body is one that absorbs radiation from its environment and then reemits all of the incident radiant energy after changing the distribution of energy as a function of wavelength to match the temperature of the black body. The result is called a Planck spectrum by physicists. The maximum intensity of the energy distribution in such radiation at 2.726 K is invisible to the naked eye, and can be seen only by instruments called radiotelescopes which are sensitive to the microwave region of the electromagnetic spectrum. (The Kelvin temperature scale is one in which zero is the absolute zero of nature; on the more familiar Celsius scale this absolute zero is at 273.155 degrees below the freezing point of water. The element helium liquefies at 4 K at atmospheric pressure. Room temperature, at 68 degrees Fahrenheit, is equivalently 20 degrees Celsius or Centigrade and 293 K) Thus blackbody radiation at 2.726 K can be visualized as the purely thermal or heat radiation emitted by a body at that temperature. By contrast, the sun is a blackbody radiator corresponding to a temperature of 5700 K

In 1948, Robert Herman and I in one of our first publications together, predicted that such a cosmic background radiation should pervade the universe if the Big Bang model is correct. On the basis of other cosmological parameters in use at the time, we calculated that this radiation should be at five K It was a great personal thrill when this prediction was observationally verified in 1965 by Arno Penzias and Robert Wilson of the Bell Telephone Laboratories. They received the 1978 Nobel Prize in Physics for this observation, and indeed the great value of their observation was that many scientists were immediately convinced that the Big Bang model was indeed a useful model of the universe. There have been many verifying measurements by other astronomers since the 1965 work, including in a spectacular way the recent measurements made aboard the COBE (Cosmic Background Explorer) satellite, a NASA polar-orbiting satellite designed for specific studies of the cosmic background radiation. The equivalent blackbody temperature of this pervasive radiation is now the most precisely known of cosmological paramet~rs, namely, 2.726 K

There has been no acceptable alternative physical explanation for this radiation other than it is indeed a fossil of the early Big Bang, a very much cooled (more correctly, red shifted) relic of the radiation pervading the universe some hundreds of thousands of years after the Big Bang, just as we proposed in 1948. A noted mathematician named Paul Erdos is quoted as having said that

"God made two mistakes; he started the universe with a Big Bang, and then he left the three degree radiation behind as evidence."

What, Then, Is The Big Bang Model?

The model describes a universe which is dynamic and evolving, starting from an extremely hot and dense state at a finite time in the past and expanding and cooling to what we see now. It is based on Einstein's theory of general relativity, from which one can derive a mathematical relation, frequently called the Friedmann Lemaitre equation, showing how physical parameters in the universe change with time. Examples of such parameters include the separation of any pair of points arbitrarily selected in the universe, the smeared-out density of matter, as already described, and the mass density of radiation. The radiation density can be calculated from a knowledge of the temperature, which is in turn related to the age of the universe, i.e., the elapsed time since the Big Bang.

We can visualize cosmic evolution by using the Friedmann Lemaitre equation which models the universe forward or backward in time and can be used either way, much as a motion picture can be viewed in either direction. Consider then, running the movie back to one second after the Big Bang, when the universe had expanded and cooled from conditions of high temperature and density which are almost unimaginable down to a temperature of some ten billion Kelvin and a density about a million times that of water, also difficult to comprehend. This density was almost entirely due to the mass equivalent of the energy in the light or radiation which was present (call the radiant energy E; then, according to Einstein's famous formula, $E = Mc2$, energy is equivalent to mass M; with the constant of proportionality being the square of c, the velocity of light) with the density of matter being that of just a trace amount (more than a million times less dense). At this time of about one second this trace amount of matter in the form of neutrons, protons, electrons and a variety of other particles such as neutrinos, had evolved from earlier and more extreme conditions of temperature and density, with matter being in the form of more elementary relativistic particles.

Having returned to a time about a second after the Big Bang, consider time reversed once again to go forward. Before about one second, the temperature and density were so high that neutrons and protons which collided and tried to coalesce were torn apart by other collisions and by radiation as fast as they could interact and form nuclei. After about one second, the particles present still collided with one another violently because of the high temperature as well as frequently because of the high density, but nuclear reactions could ensue because the collisions were no longer so energetic as to break apart all new nuclear species formed. Details of such reactions can be studied in high energy laboratory particle accelerators or (carefully) inside a thermonuclear bomb. The capture of neutrons by protons represents the first step in the build up of nuclei, including heavy isotopes of hydrogen, namely deuterium and tritium (these each contain one proton, but one and two neutrons, respectively) as well as normal helium and its light isotope helium three, and a small amount of lithium. These so-called thermonuclear reactions are stopped by the continuing universal expansion which reduces the probability of collisions as the particle densities drop, by the cooling in the expansion which reduces the energy of collisions, and by the radioactive decay of neutrons into protons, electrons and neutrinos, which removes neutrons which would otherwise be involved in reactions. The neutron has a half-life of 880 seconds; if you start with a given amount of neutrons, half of the neutrons would undergo decay in 880 seconds. Clearly this decay limits the time available for neutrons to be involved in reactions. All of this nucleosynthesis occurred in a time period from about a second to about five minutes into the Big Bang.

Following primeval nucleosynthesis, nothing much of interest occurred during the next hundred thousand to a million years. During this transition epoch the rate of expansion was controlled by the radiation present because of its much higher density in the early universe, and the state of the universe was that of a plasma containing trapped radiation. To reiterate, the plasma consisted of stripped hydrogen atoms (a proton ion and a free electron), stripped helium atoms (the helium ion and two free electrons each), the whole being a fully ionized gas which on average had no net electrical charge. After a hundred thousand to a million years or so, the temperature dropped to several thousand degrees, sufficiently low for the free electrons to attach to the hydrogen and helium nuclei, and the gas then transformed from a plasma state to a neutral gas, a transition process called recombination. This was the first time in the history of the universe that neutral atoms appeared.

Several phenomena are associated with this era of recombination. For one, while the gas is still a plasma, radiation could not travel very far before it was deflected or scattered by bouncing off of charged particles, and the system is said to be opaque - the radiation is effectively trapped in the plasma. When the gas became neutral, the radiation could travel more freely. The universe had become transparent, and matter and radiation were decoupled. Moreover, the radiation emerged at this time with the same degree of homogeneity and isotropy as the matter in the plasma state during the time of last interaction of the radiation with the plasma. The second noteworthy phenomenon is that it is very near the conditions of recombination when the nature of the expansion changed to one controlled by the density of matter, for it is just during this epoch that the density of radiation dropped to a value below that of matter. This cross-over occurred because the radiation density decreased more rapidly with the cosmic expansion than did the matter density.

It is important to emphasize that the decoupling allowed the noninteracting and therefore freely propagating radiation to retain and reflect any small departures from homogeneity and isotropy in the spatial distribution of matter that existed in the universe at the time of decoupling. It is just such small departures, at the level of about ten parts per million, which have been recently reported with considerable excitement as new measurements made from the COBE satellite, and it is just these small departures which were hoped for by cosmologists to act as seeds for the later gravitational agglomeration of matter into galaxies and clusters of galaxies. Were there absolute homogeneity, or departures significantly smaller than those now suspected, it would be difficult to construct a theory which would lead to the formation of galaxies in the time allowed by the age of the universe.

The decoupled radiation has freely expanded from the recombination era until to day. Expanding radiation also cools, and the radiation has cooled from several thousand Kelvin at the time of decoupling to the 2.726 K background measured today. Note that neutrinos, the very light or massless particles which I mentioned earlier should, according to theory, have persisted to today, cooling with the expansion, and should be pervasive in the universe at energies corresponding to a temperature of about 2 K. With present technology it does not appear possible to detect such cold neutrinos, even though calculation suggests there should be several hundred such neutrinos per cubic centimeter. We have to be cautious here, for prior to .the measurements of Penzias and Wilson, the possibility of observation of the relict radiation was similarly doubted. There might, in addition, be pervasive gravitational waves, also left over from the early universe, and also with observability highly unlikely. Thus we have several observed fossils of the early universe, including the cosmic abundance distribution of the light elements and the cooled radiation from the recombination era which exhibits tiny departures from uniformity.

Formation Of Structure

The tiny deviations from homogeneity in the universe at the time of last interaction of radiation with matter, as now observed by COBE, represent small local excesses or fluctuations of density, which can act as seeds for the gravitational condensation and growth of the various structures in the cosmos. It had been considered a problem of the Big Bang model that the cosmic background radiation appeared to be so uniform, since it has been the view of cosmologists that some kind of seed for condensation was required to allow the observed structure in the cosmos to develop in the time available. Now such seeds have been detected. Unfortunately our detailed view of these seeds is not yet good enough to enable one to select among the several models which have been proposed for the formation and evolution of structures. COBE data continues to be analyzed, and perhaps in the near future the needed detailed understanding of these seeds will be available. At least for now the scientific question is no longer how structure developed without seeds to start condensations, but, instead, what the details of the formation of structure may be. Details of the several theories of the formation of structure are beyond the scope of this essay.

The Very Early Universe

In recent years the physics of the very early universe, roughly the time "long" before one second of the Big Bang had elapsed, has become a very popular area of research for scientists interested both in high energy and elementary particle physics as well as cosmology. The projected physical conditions in this regime are well beyond the reach of experimental laboratory devices, present

·or projected, although there is reason to believe that experiments run under less severe conditions will provide insights to guide theoretical exploration of the very early universe. This had been one of the driving forces for the construction of the late Superconducting Super Collider (SSC). Moreover, there is theoretical and experimental interest in this regime because it may shed light on the current search for a fundamental unity in the forces of nature. The search for this unity occupied Einstein for most of his scientific career. Finally, there is always the hope that a study of this regime-will yield predictions of phenomena which might be seen in forthcoming observational cosmological studies. It is almost staggering to the imagination to realize how our capabilities for such studies have increased in recent decades, how much we are now studying and discovering about the cosmos which was not even dreamed of before, say, 1960, such as the background radiation, pulsars, quasars, interstellar molecules, galaxies with highly luminous central regions, putative black holes, and the like.

From the work already done on the very early universe, it appears that one can explain the enormous preponderance of matter over antimatter in the cosmos. Let me explain this idea further. It is a feature of nature that each kind of elementary particle has a concomitant antiparticle with some properties inverted. Thus the proton, the nucleus of the hydrogen atom which carries a single positive electric charge (quantitatively the same charge which is carried by an electron), has an antiproton counterpart which is the same except that it carries a single negative electric charge of the same magiritude. The electron, which carries a single negative electric charge, has an antiparticle counterpart called the positron, which is the same except for the sign of the charge.

The antiparticle concept is the same for all elementary forms of matter; thus, the neutron has the antineutron, the neutrino has an associated antineutrino, and so on. There has been considerable concern that whatever processes go on in the very early universe should, on the basis of general arguments for symmetry in nature, produce equal amounts of matter and antimatter, and yet there is no evidence for the natural occurrence in the cosmos of antimatter at greater relative abundance with respect to matter than one part in ten million. One of the exciting results of recent studies of the physics of the early universe has been that there could have been symmetry breaking which led to the great preponderance of matter over antimatter.

The Inflationary Early Universe

There is a relatively new theoretical development which promises to eliminate some of the unresolved questions posed by the standard Big Bang model. This new set of ideas has been called the "inflationary" model, which addresses the structure and evolution of the universe at extraordinarily short times after the Big Bang when the standard model of the Big Bang extrapolated back in time is not expected to apply. It introduces for a very short early time an expansion rate completely unlike and enormously greater than that which one finds later in the standard Big Bang model. Inflation is in fact a theory, or more correctly at the present time a collection of theories, of what may have happened in the very early universe, at times small compared even with a fraction of a second after the Big Bang; it is taken as required that all such theories must merge comfortably into the standard Big Bang at later times.

There is some hope that more detailed COBE data now accumulating as the instruments aboard the satellite continue to measure background radiation will in the end make it possible to choose among the several optional views of the nature of the very early universe, as well as among the several theories of the formation of structure. Moreover, ground-based radiotelescope observations such as those currently being pursued in the Antarctic, should also increase our understanding of the departures from isotropy in the region of last interaction of matter and radiation, the era of decoupling.

Origin Of The Universe

Inflation theories suggest the probable existence of a very short period when the dimensions of a small volume containing all that is now observable in principle in the universe underwent a violent expansion. Our present knowledge of physics does not permit us to discuss in a definite way what may have occurred prior to the onset of inflation, at a time of the order of 10-43 seconds, an arcane number whose derivation is beyond the scope of this essay. Almost certainly events prior to and at this very early time can only be understood in terms of the quantum behavior of matter and of gravity, since the size of what we now call the universe was small even as compared to regions in which quantum mechanical effects predominate in our common laboratory experience.

All of this is quite speculative, and highly dependent on an improved knowledge of the average density of matter plus radiation in the universe and of the rate of expansion - the Hubble parameter. These two parameters fix the value of the critical density with which the present average density must be compared to distinguish among the several types of expansion. I would note that one can argue with some justification that at least in the standard model of the Big Bang the reactions among the particles and radiation prior to the onset of nucleosynthesis proceeded more rapidly than the expansion, so that the reactions kept up with changing conditions, and the universe was in a state of equilibrium. One chMacteristic of a true state of equilibrium is that it wipes out previous history. In general you can not ascertain from an equilibrium state the previous history of the state. As an example, consider that all the gas molecules in the room in which you now find yourself were confined initially to a small volume in the corner of the room. The confinement is removed, and the gas molecules diffuse and ultimately fill the room uniformly. In this state the gas would be in equilibrium, and there are no measurements which would make it possible to learn anything about the initial state. It may be more nearly correct to suppose an early cosmic state very near equilibrium, for work already done on the very early universe suggests that some events occurred whose effects survived through the period of light element production, such as the predominance of matter over antimatter.

A question most frequently asked is - what came before the onset of inflation. The simplest answer is that we do not know. Perhaps a more relevant response might be that this is not a sensible question, since the present view is that space, time and matter may well have been generated at the Big Bang. The major question with regard to the Big Bang, or for any model of the universe we construct, is the uncertainty about what we will learn from our rapidly increasing capabilities in observational astronomy. It would be exciting to come back in, say, a hundred years to see what new observations have said about the validity of the model. Thus far we can only say that the model has survived very well for at least four decades.

The Future Of The Universe

To quote a famous physicist, Niels Bohr, "Prediction is very hard, particularly of the future." But I would remind you that we could say something about the future at several levels of detail. Unfortunately, no one reading this essay now or for a long time to come will be able to say whether there is any truth in the predictions. While the universe is indeed dynamic and evolving, change occurs on a very slow time scale in either human or astronomical terms. If we are sure ultimately that the universe is homogeneous and isotropic on a very large scale, and if we have tied down our estimates of the average density of matter and the expansion rate, we can then say whether the universe is open, flat or closed, i.e., whether the universe will continue to expand and cool, or whether it will ultimately slow down, stop, reverse and go into a Big Crunch. We can provide some guesses about the future of matter and energy, but there are many possibilities and it would really take us far afield to describe them. Present data suggest the universe will continue to expand and cool indefinitely.

Closer to home, we are at the mercy of the evolution of the Sun. On the basis of our present understanding of stellar evolution, the Sun will continue in its presently stable state for billions of years, and if *homo sapiens* takes care of itself, other species and the environment, we can expect future generations to gain further insights into the origin and evolution of the universe. Perhaps by the time the Sun goes into its next phase of evolution, billions of years hence, in which it is expected to be a red giant with an expanding envelope approaching or engulfing the earth, *Homo Sapiens* will have colonized elsewhere in the Milky Way and be resident on safe planets.

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SUGGESTIONS FOR FURTHER READING

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Epilogue

What does the Big Bang model of the universe have to say about some of the fundamental questions that many people raise after becoming acquainted with the model? It seems to me that one can reduce these fundamental questions to two in number, viz.,

- What is the role or place of *homo sapiens* in the universe?

. Can the existence of an extramundane entity which now directs the evolution of the universe, or was responsible for establishing the universe, be considered to be a consequence of what has been deduced by scientists from theoretical and observational studies of the universe?

Let me deal with the first question. Those who study the physics of the universe find it to be, in human terms, a most inhospitable place. Within and around stars, matter and radiation exist at such high temperatures and densities as to preclude the existence of all but the simplest molecules - certainly not those we associate with life forms. Between stars we find very low temperatures, and very tenuous matter mostly in the form of the elements hydrogen and helium, but there also exist complex molecules in very low concentrations whose counterparts or derivatives are found in the materials in life forms. This is a long way from saying there are life forms in interstellar space, but one could nevertheless argue that the seeds of life forms do exist in interstellar space, and that life might evolve on planets of whose existence we are not aware. I would note that there has been a recent observation best interpreted as showing three or four objects of planetary mass orbiting a pulsar - an evolved star in whose neighborhood conditions must almost certainly be most inhospitable to life as we know it.

For the moment we know only that sentient life forms exists on the surface of the earth, where this life appears to have evolved in such a way as to survive in the rather narrow range of physical conditions one finds here. Scientists do not yet have a totally acceptable model of the entire course of evolution, There is general agreement on evolution driving the development of species, but the "devil seems to lie in the details." Nevertheless there does not appear to be any reason to despair of the further development of the theory of evolution. As just mentioned, evidence is beginning to emerge for the existence of planets elsewhere in the universe, but we are a long way from really demonstrating the existence of life forms (organisms with the capability of replication) elsewhere. One must be careful here; most scientists would consider it the height of anthropocentrism to conclude that humankind is the only sentient life form in the universe.

The essence of these remarks is that most people who study the physics of the universe conclude from the evidence that the universe is utterly indifferent to the presence of life on earth. That there are life forms on earth which can wonder about the reasons for their existence does not lead necessarily to the conclusion that there is some reason for such existence. It appears to be simply a consequence of evolution that there now exist life forms capable of self-awareness and of concern about the reasons for existence. And now to the second question. Must we invoke an extramundane entity to make sense of it all, to start things off, at least, or to direct the course of events throughout the history of the universe? If one looks at the history of the universe as a series of cause-effect events, should there not be a first cause, which, treated as an event, in fact requires no precedent cause? I submit that it is a "cop-out" to argue that this entity has existed forever, and therefore does not require an explanation of the first cause. I recall well that there was for many years an argument by advocates of the so-called "steady-state model" of the universe which demonstrated that they could not deal on a philosophical basis with a universe whose origin was located at a finite time in the past. In fact they preferred to place the origin at an infinite time in the past, which they argue is beyond our ken and requires no further discussion. In order to maintain a steady state in an apparently expanding and rarefying universe they had to invoke "continuous creation" of matter uniformly everywhere, at a rate which is well beyond our observational capacity.

Should there be some "personal rapport" between this extramundane entity and the sentient life forms who are raising questions or developing cosmic views based on faith rather than on observation and the construction of verifiable models? There are many, many books dealing with these questions. One of these, by Craig and Smith[1], is in the form of a debate between a person who is a dedicated Christian (Craig), and a philosopher (Smith), who is apparently at least an agnostic, if not an atheist. Another is by S.L.Jaki[2], a Catholic priest and science historian, who is also conversant with contemporary cosmology and was trained as a physicist and theologian. I would not presume to try to cover the contents of these most recent of books. Having read them, among others on the subject, I conclude that it is fruitless for scientists to enter into arguments in which the person who looks at the universe with a vision completely obscured by faith draws on the "revealed truths" in the scriptures. Such people are completely comfortable with accepting arguments and explanations which do not offer verifiable statements. In the end those who deal with the cosmos and humankind on the basis of faith alone already have the answers they require to "accept the universe" as they find it. They may argue about specific items and events by retreating to the scriptures, when in fact the veracity of the scriptures is itself a matter of faith. Some may regard my next remarks as extreme, but I submit that the invocation of an extramundane entity is the ultimate antiscience position. The acceptance of such an entity renders moot any reasonable pursuit of understanding on the basis of scientific inquiry. It is the essence of science and of modeling of phenomena that the process is self-correcting, usually in the direction of improvement. To put it simply, a scientist makes some observations, constructs a model which he hopes will organize and rationalize the observations, checks the model against observation, and then modifies the model to do a better job. All of this is done with the. hope that the simplest conceivable model will suffice, and that one can obtain a good fit between theoretical model and observation without undue complexity or having to invoke new laws of nature. Of course, this self-correcting approach does in fact sometimes lead to new laws of nature.

As a case in point, one of the common arguments has to do, as already mentioned, with the existence of a first cause, since, some say, there must be a cause for every effect in the cosmos. But the theists or deists will not discuss the origin of the first cause, which seems to me to be a retreat to faith in the limit of this argument, and a retreat to complexity which may not be needed.

In essence, I argue that the existence of an extramundane entity is an irrelevant question in the present stage of our studies of the universe, There are those who argue that the current model of the evolving universe has problems, and that we must therefore accept the concept of God or some "ultimate reality" in order to have closure in our views. There are problems indeed; to my knowledge there are no models of physical phenomenon which do not have some problem. We may not yet be clever enough to get past a problem with our theory, or with our limited capabilities in observational science, but these issues are not sufficient reason to conclude that in the end we will not understand to any depth we may choose to pursue. To say otherwise is to say that science is done, when in fact scientific study of the universe is a relatively recent activity in the history of humankind. One has only to look at the recent output of the corrected Hubble space telescope to realize that we have hardly begun.

One other slightly different argument I would mention is that there must be some extramundane entity who established the "laws of nature" and then turned the universe loose to run its course. This has the consequence of confining God's role to the first 10^{-40} to 10^{-30} seconds of the existence of the universe. It makes one wonder about the efficacy of prayer. Others argue for a directed universe, in which God directs the evolution of the universe at every instant, so that we have nothing to do with what happens. In essence this argument states that God can and does intervene in any and all situations. This would make it very difficult indeed for *homo sapiens* to construct models and to make predictions of natural phenomena, since the rules are subject to change at any time without notice. Although the occurrence of the Holocaust for the Jews and the murder of millions of non-Jews in World War II, as well as the continuing death and destruction in Europe and Africa, is not in the purview of science, I simply cannot buy the idea that this was somehow part of God's plan. Moreover, I would argue that it is nonsensical to ascribe the laws of nature to God; on the contrary, these laws, as for example Newton's law of gravitation, Einstein's theories of relativity, the quantum nature of matter and energy, etc., are nothing more than human constructs for organizing scientific observations.

Permit me to paraphrase the words of a friend of mine, the late Rev. William J. Gold, who was a distinguished Humanist, viz., "I don't know if there is a God, and even though I regard the concept as irrelevant, there is no harm in trying to live my life as though there were a God. If there is a God, surely he will be a forgiving God, and will forgive me for doubting his existence. If there is no God, I've lost nothing." I would add that if one argues for a God who started the universe off, and has let it run its course since, then one argues for a concept which is wholly irrelevant.

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