The Anthropic Principle

Certain conditions, such as temperature, were favorable to the emergence of life on the earth. The anthropic principle argues the reverse: the presence of life may "explain" the conditions

by George Gale

The earth is an exceptionally hospitable place for mankind, with abundant water and an average temperature that happens to lie in the narrow range where water is a liquid. In view of the evolutionary origin of life, these facts are hardly surprising; if the earth were cold and dry like Mars, or if it had a steaming, caustic atmosphere like that of Venus, intelligent beings would not have evolved to remark on the hostility of their surroundings. It seems decidedly odd, however, to argue that the presence of life on the earth might "explain" why the planet has a temperature between the freezing point and the boiling point of water. The usual practice has been to argue the opposite proposition, namely that life evolved on the earth because the circumstances were conducive to its existence.

Although the reasoning may at first seem backward, the idea that the mere presence of intelligent life can have some explanatory power has recently been introduced into cosmology, where the task is to understand the history not of a single planet but of the entire universe. It is easy to imagine a universe quite different from the observed one. For example, changing the values of certain physical constants might give rise to a universe where the chemical elements heavier than helium are never formed or where all stars are large, hot and short-lived. In most such imaginary reconstructions of the universe it is unlikely that an intelligent form of life would ever appear. The fact that the real universe does harbor intelligent observers therefore places certain constraints on the diversity of ways the universe could have begun and on the physical laws that could have governed its development. In other words, the universe has the properties we observe today because if its earlier properties had been much different, we would not be here as observers now. The principle underlying this method of cosmological analysis has been named the anthropic principle, from the Greek *anthropos*, man.

The mode of reasoning embodied in the anthropic principle is quite different from the deductive mode that has long been characteristic of much scientific thought. A deductive theory begins by specifying the initial conditions of a physical system and the laws of nature that apply to it; the theory then predicts the subsequent state of the system. For example, one might deduce the present conditions on the earth by specifying the initial size, mass and chemical composition of the nebula from which the solar system condensed, then tracing the evolution of the sun and the planets under the influence of physical laws that describe gravitational forces, nuclear reactions and so on. The anthropic principle has been invoked in cosmology precisely because the deductive method cannot readily be employed there. The initial conditions of the universe are not known, and the physical laws that operated early in its history are also uncertain; the laws may even depend on the initial conditions. Indeed, perhaps the only constraint that can be imposed on a theory reconstructing the initial conditions of the universe and the corresponding laws of nature is the requirement that those conditions and laws give rise to an inhabited universe.

At the least the anthropic principle suggests connections between the existence of man and aspects of physics that one might have thought would have little bearing on biology. In its strongest form the principle might reveal that the universe we live in is the only conceivable universe in which intelligent life could exist. It is fair to say, however, that not all cosmologists and philosophers of science assent to the utility of the anthropic principle, or even to its legitimacy. Here I shall describe some of the ways in which the principle has been applied and let the reader judge its validity.

The concept that underlies much of modern cosmology is called the Copernican principle. Its origins can be traced to the assertion made in 1543 by Nicolaus Copernicus that the earth is not the center of the universe. The modern, extended form of the principle was not stated explicitly, however, until 1948 by Hermann Bondi of the University of Cambridge. It holds that the position of human observers in the universe is not in any way privileged or especially distinguished from other positions; hence observations in cosmology are valid not only for the earth or for the solar system but also for remote regions of the universe. The Copernican principle or some assumption like it is methodologically necessary in cosmology; without it cosmological findings could be dismissed as idiosyncrasies stemming from physical features peculiar to the fraction of the universe inhabited by human observers. Of course, as Bondi himself recognized, the usefulness of the Copernican principle is no guarantee of its truth.

A generalization of the Copernican principle has come to be known as the cosmological principle. It states that not only is the position of the solar system without privileged status but furthermore no position anywhere in the universe is privileged. Implicit in this idea is the assumption that the large-scale structure of the universe is uniform: apart from local irregularities, such as galaxies, all regions of the universe are exactly alike. A homogeneous structure is appealing (in the absence of evidence to the contrary) because it is the simplest possible structure. On this methodological assumption the earth occupies a typical position in space.

Evidence for the cosmological principle comes from the reproducibility of most scientific experiments. Even when an experiment, such as a measurement of the speed of light, is done repeatedly in the same laboratory, it is nonetheless being done both at different times and at different points in space (because the earth has moved in the interim). Insofar as the results are the same, the position of the earth does not affect the experiment. Such evidence is less than convincing, however, because conclusions in cosmology pertain to regions

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of space-time much larger than those traversed by the earth.

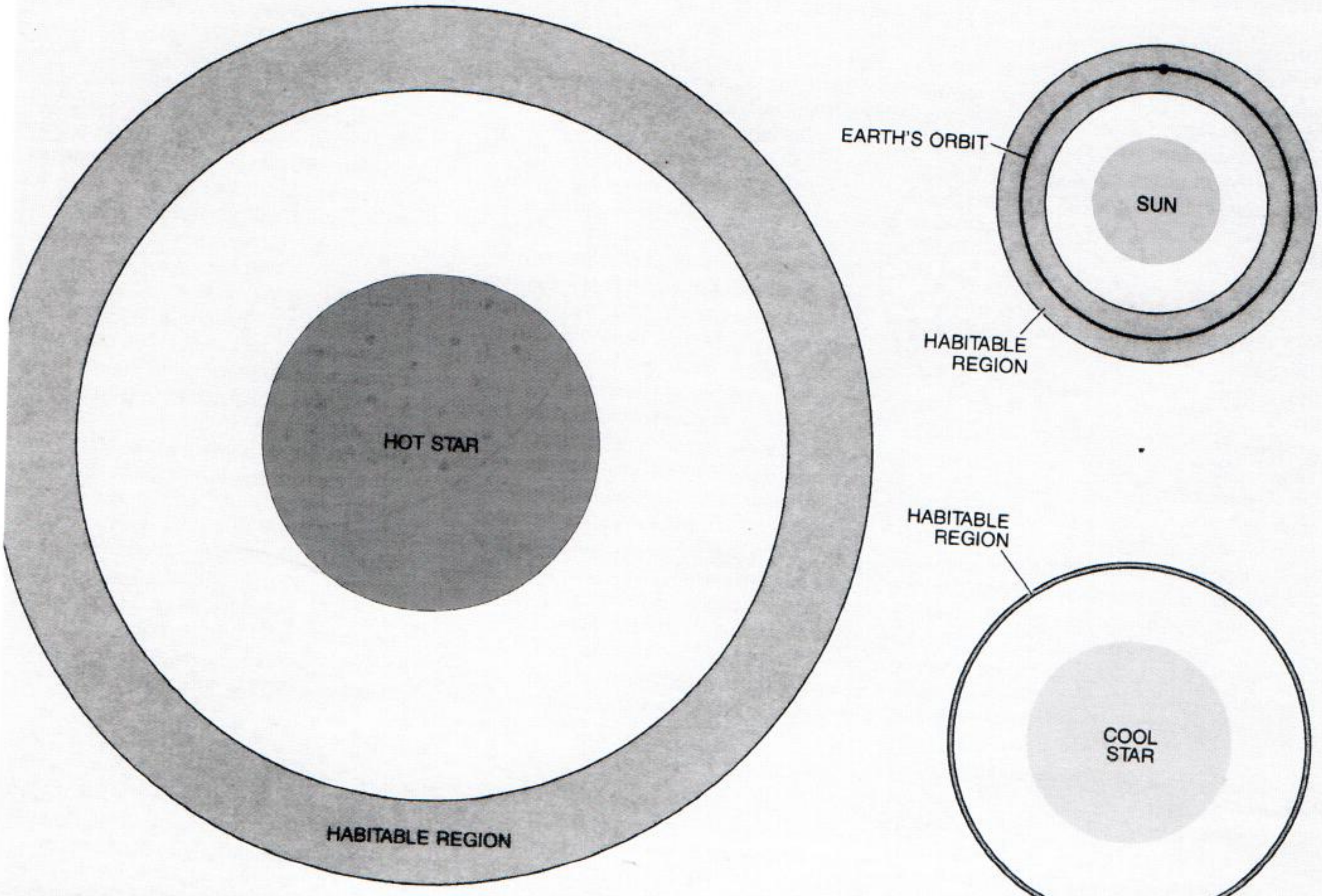
Bondi and Thomas Gold of Cornell University proposed a still more general assumption called the perfect cosmological principle. It states that apart from local irregularities the universe is uniform both in space and in time, so that an observer would see the same large-scale structure from any place and at any epoch. The perfect cosmological principle is the basis of the steady-state model, which in its original formulation posited a universe completely uniform throughout space and time. In order to accommodate evidence that the universe is expanding, the model assumes that matter is being created continuously. The steady-state model has since largely been abandoned and as a result so has the perfect cosmological principle. The cause was the detection in 1965 of the universal background of microwave radiation. The microwave background is interpreted as the remnant of a stage in the early universe when it was much hotter and denser than it is now.

Although the microwave background radiation rules out the temporal uniformity of the universe, it provides the most compelling evidence for large-scale spatial uniformity. The observed radiation is isotropic—that is, it comes from all directions with equal intensity—to an accuracy of better than one part in 1,000. Thus the properties of the background radiation support the cosmological principle but not the perfect cosmological principle.

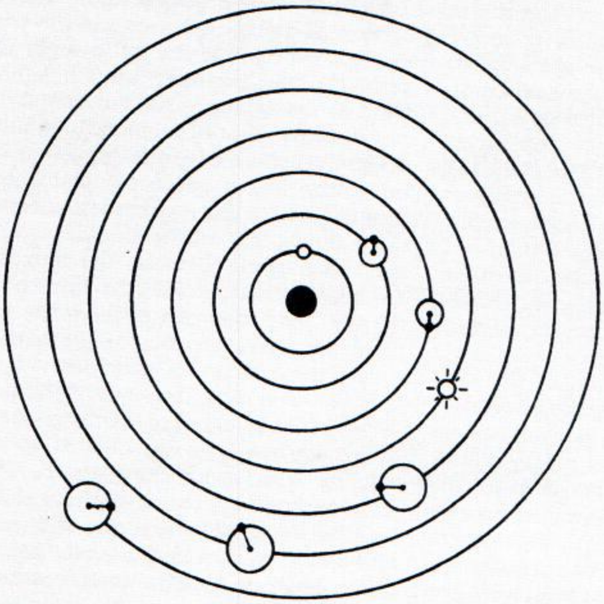
The observed expansion of the universe is also consistent with the cosmological principle. The expansion has no center: an observer in any galaxy would see all other distant galaxies in all directions receding from him. The farther away a galaxy is, the greater its velocity of recession is. For galaxies at the same distance the recessional velocities are equal within an accuracy of better than one part in 1,000.

The microwave background, the recession of distant galaxies and the cosmological principle are all brought together in the big-bang model, which takes as the origin of the universe a dimensionless point of apparently infinite density. Such an origin is suggested by imagining the current recessional velocities to be reversed; extrapolating backward shows that all the galaxies would meet at a point. Because the universe has been expanding since the moment of the big bang, one can estimate its age from the characteristics of the expansion. If the recessional velocities had not changed over time, the age of the universe would be equal to the distance between any two galaxies divided by the velocity with which they are receding from each other. This hypothetical age is called the Hubble time, after Edwin P. Hubble, who in 1923 discovered the relation between distance and recessional velocity.

Actually it is likely that the recession-



ABITABLE STAR SYSTEMS include only those in which a star ats up a region of space where the temperature falls in the narrow nge in which water is a liquid. In the diagram at the left is the warm- t star whose planets could support intelligent life; in the diagram at e upper right is the sun; in the diagram at the lower right is the cool- t star whose planets could support intelligent life. (In each diagram e star and the planetary system are drawn to a different scale.) The per and lower limits on the size of a life-supporting star arise from ferent properties of the stellar systems. A larger and brighter star uld provide a habitable region, but the star would remain in a sta- stage of its evolution too briefly for life to evolve. A smaller and dimmer star could also provide a habitable region, but the planet would be too close to the star. As a result of tidal interactions the planet would stop rotating and an extreme temperature difference would develop between the light side and the dark side. Ultimately the planet's atmosphere would be boiled away on the light side and frozen on the dark side. Life evolved on the earth because of the circumstance that it happens to occupy a habitable region. The anthropic principle argues the opposite proposition, namely that the presence of life on the earth explains why the planet has a temperature in the narrow range where water is a liquid. It remains to be seen whether the anthropic principle will win general acceptance among cosmologists.



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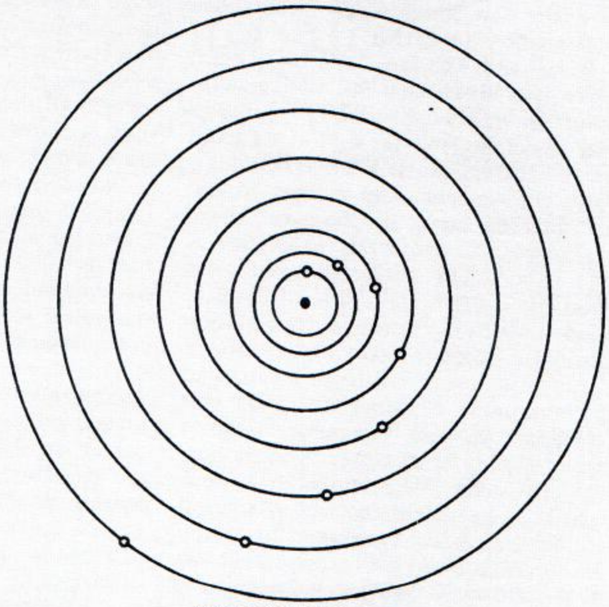
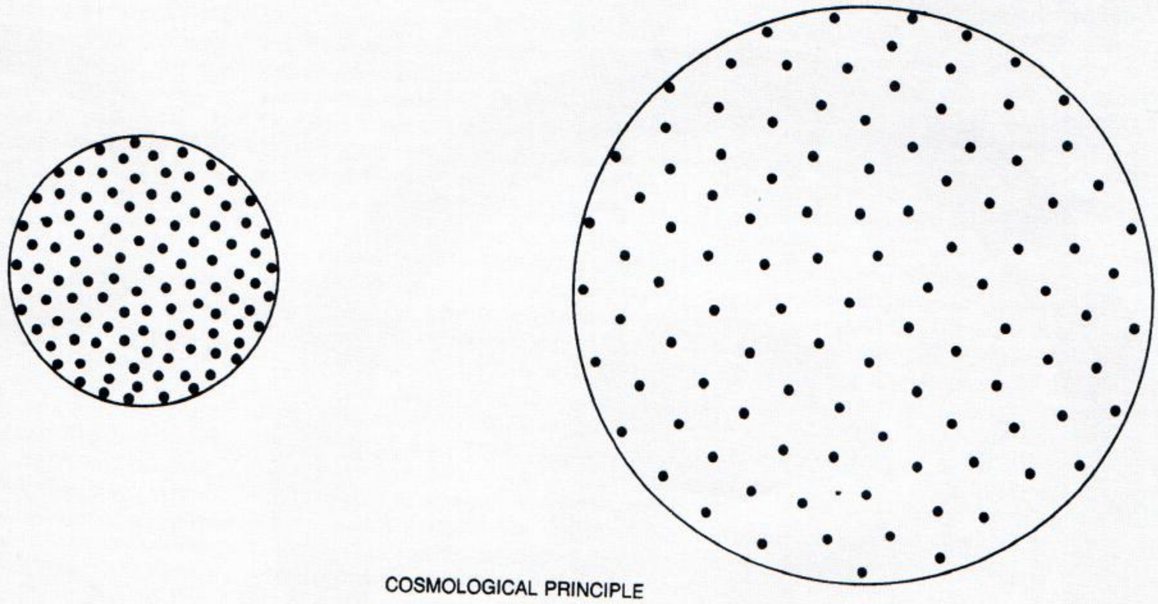
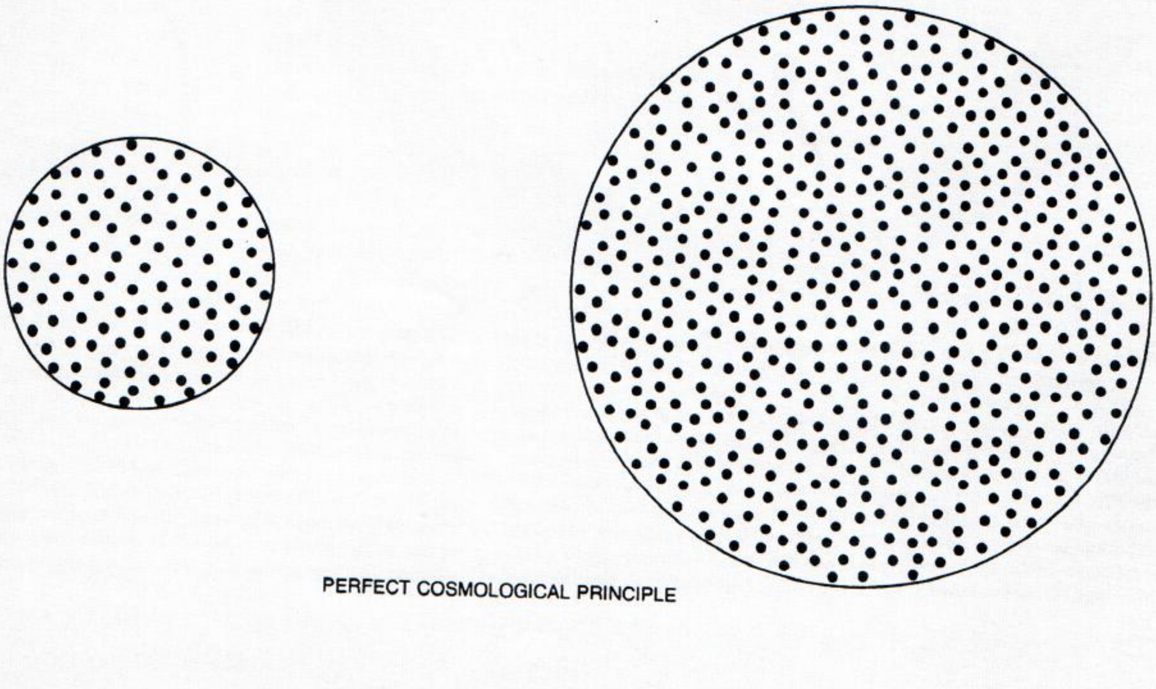


COPERNICAN SYSTEM



COSMOLOGICAL PRINCIPLE



PERFECT COSMOLOGICAL PRINCIPLE

l velocities have changed, although it is ot clear by how much. One cause of uch change is the mutual gravitation- l attraction of all the galaxies, which ends to slow the expansion of the uni- erse. The change in the rate of expan- ion in the period since the big bang de- ermines whether the universe is "open" r "closed." An open universe will ex- and forever. A closed universe will ventually stop expanding, start con- racting and ultimately collapse in a "big top." If the universe is open, the current xpansion rate suggests its age is rough- y 20 billion years. If the universe is losed, the rate of expansion suggests it s about 13 billion years old.

The anthropic principle was introduced by Robert H. Dicke of Prince- on University in 1961; he proposed it in he course of analyzing work done by . A. M. Dirac some 30 years before. irac had called attention to certain cu- ious numerical relations among dimen- ionless numbers that have an important ole in physics and astrophysics. A di- ensionless number is one that has no nits of measurement associated with it, o that its value is the same in any sys- em of measurement. Dirac did not con- ider the exact value of the numbers but nly their order of magnitude: the pow- r of 10 that most nearly expresses the alue. He found several instances where e order of magnitude is an integral ower of the large number 10^{40}.

Three numbers that figured promi- ently in Dirac's work are measures of rce, time and mass. The first quantity a dimensionless form of the gravi- ational coupling constant, which is a easure of the strength of the gravita- onal force; it has a value of roughly 0^{-40}. The second dimensionless num- er is the age of the universe expressed atomic units: Dirac defined it as the atio of the Hubble age to the time re- uired for light to traverse a distance qual to the radius of a proton. The ratio as a value of roughly 10^{40}. (Because irac was concerned only with the or- er of magnitude, the Hubble age and the other age estimates yield much the same result.) The third dimensionless quantity is the number of massive particles (such as protons and neutrons) in the visible region of the universe; the number is estimated to be about 10^{80}.

Dirac noted three order-of-magnitude relations among these quantities. First, the gravitational coupling constant is the reciprocal of the age of the universe in atomic units. Second, the number of massive particles is the square of the age of the universe in atomic units. Third, the gravitational coupling constant is the reciprocal of the square root of the number of massive particles. Dirac thought the numerical relations were too striking to be dismissed as coincidences. He proposed that they are a manifestation of some unknown causal connection.

One possible objection to these ideas is that the age of the universe obviously increases with time. As a result the relations of the numbers should be continuously changing, and it is an extraordinary coincidence that their values should be determined just when they fall into correspondence. Dirac forestalled this criticism by proposing that the gravitational coupling constant and the number of massive particles also change with time in such a way that the order-of-magnitude relations remain valid throughout the history of the universe. For the correspondences to persist gravity must grow weaker in inverse proportion to the time and the number of particles must increase in direct proportion to the square of the time.

Dirac's analysis was generally received with little enthusiasm, but Dicke took it seriously. He proposed that a causal connection between the gravitational coupling constant and the number of massive particles might be founded on a principle first enunciated by Ernst Mach. Mach had proposed that the inertial mass of a particle is determined by its gravitational interaction with distant matter. (The established view was that inertial mass is a property of the particle quite independent of its surroundings.) According to Mach's principle, the weakness of gravitation is related to the enormous amount of distant matter in the universe. If the principle is accepted, it is not surprising that there should be some numerical relation between the gravitational coupling constant and the number of massive particles, which is a measure of the amount of matter in the universe.

It is not apparent, however, why the coupling constant and the number of particles should be related to the Hubble age. On the contrary, if Mach's principle is valid at all, it should remain valid in all eras in the history of the universe, whereas the order-of-magnitude relations would be observed only in the present era. Again, it seems man has appeared at a privileged and therefore unlikely moment.

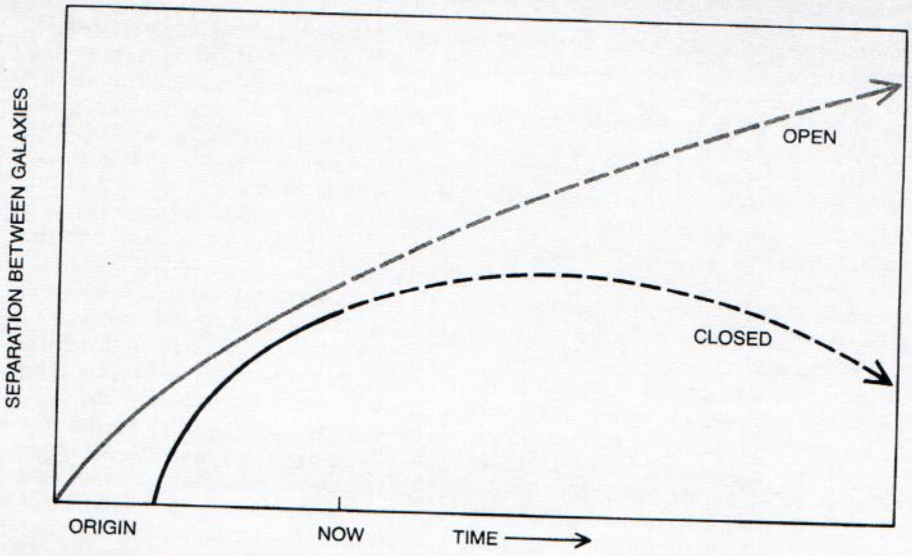
Dicke's answer to this objection was that the value of the Hubble age is strongly constrained by the conditions necessary for the existence of man. One essential condition is that the universe should have aged enough to allow time for the creation of elements heavier than hydrogen, because "it is well known that carbon is required to make physicists." Heavy elements are made in the interior of stars and are released when a star explodes as a supernova. Consequently the Hubble age of an inhabited universe cannot be shorter than the age of the shortest-lived star. On the other hand, if the Hubble age were much greater than the age of a typical star, most stars whose planets could support life would have died by now. Therefore, Dicke concluded, the Hubble age is roughly equal to the life span of a typical star.

The novelty of Dicke's argument deserves close analysis. Given the existence of man, he argued, the Hubble age could not have a value much different from the one it actually has. Hence Dirac's numerical relations apply not to any possible evolutionary universe (where the Hubble age could presumably take on any one of many values) but only to the universe that is observed by physicists today.

One of the most appealing features of Dicke's analysis is its apparent demonstration that the value of the Hubble age is not arbitrary. Reducing the arbitrariness of explanations is a long-standing aim of the sciences, and so in this respect Dicke's work is not unusual; what distinguishes it is the method or the logic of the argument. In general arbitrariness has been eliminated by showing that a phenomenon can be predicted or that a theory can be deduced from some more fundamental premise. Dicke's technique is quite different.

Deductive or predictive logic proceeds from a fundamental assumption to a derived result: the future is deduced from the past. The temporal flow of

ODELS OF THE UNIVERSE prevalent at various times in the past 2,000 years are dia- ammed in order of increasing symmetry. In the Ptolemaic system, codified in the second cen- ry A.D., the earth has a fixed position at the center of the universe and all other celestial dies circle the earth. In 1543 Nicolaus Copernicus suggested that the center of the universe not the earth but the sun. In the 20th century the universe was discovered to be expanding iformly in all directions, and so the idea that the universe has a center was abandoned. The smological principle holds that the large-scale features of the universe would appear the me to an observer in any galaxy looking in any direction. The schematic diagram of the cos- ological principle shows the expanding universe at two times; each dot represents a galaxy. o matter which galaxy is singled out, all other galaxies recede from it; as the universe ex- nds, the distance between galaxies changes but their geometric distribution does not. The rfect cosmological principle presents a universe that is even more symmetrical: the large- ale features are the same not only from every point in space but also from every point in time. the version of the perfect cosmological principle diagrammed here the universe expands but w galaxies form just fast enough to maintain a constant density. The perfect cosmological inciple has now largely been abandoned. The anthropic principle, which is not diagrammed, serts that the earth is a privileged position because intelligent life is present on the planet.



AGE OF THE UNIVERSE can be estimated from the characteristics of the current expansion. The diagram shows the separation between galaxies as a function of time. The point labeled "Now" corresponds to the current rate of expansion. From the present rate alone, however, the age of the universe cannot be deduced. The rate has probably diminished since the big bang because of the gravitational attraction of the expanding matter. It is not known whether the expansion will continue forever (*colored curve*) or whether eventually the universe will stop expanding and then collapse under its own gravitation (*black curve*). Either possibility is consistent with the available evidence and with the big-bang model. Continued expansion suggests an age of some 20 billion years; expansion followed by collapse gives an age of about 13 billion years. The age estimated by assuming a constant rate of expansion is the Hubble time.

Dicke's argument is in the opposite direction. He cites a present condition (man's existence) as the explanation of a phenomenon grounded in the past (the age of the universe). Clearly his result cannot be interpreted as a prediction, since it would be a prediction of the past on the basis of that past's own future.

Cosmologists have turned to the anthropic principle because it is difficult to apply predictive logic to the early universe. A deductive explanation in cosmology would presumably show how observed features of the universe, such as the distribution of matter or the value of the gravitational coupling constant, are not arbitrary but instead follow from some underlying principle. Such an explanation is difficult to provide because it requires knowledge of the initial conditions of the universe.

One observed feature of the universe that stands in need of explanation is its isotropy. C. B. Collins and Steven W. Hawking of the University of Cambridge have found that in current models of the universe only a few sets of initial conditions out of the many conditions possible could give rise to the observed isotropy. Any theory in which the isotropy is deduced or predicted must begin by postulating such highly arbitrary initial conditions. Collins and Hawking find this result unsatisfying, because it offers no compelling reason for the universe's having turned out the way it has and not otherwise. What is needed is some prior constraint that would explain why the initial conditions had to be among those few that lead to isotropy; a prior constraint on the initial conditions of the universe, however, is almost inconceivable. Investigators have therefore resorted to the anthropic principle, which limits the class of possible initial conditions not by a prior constraint but by a subsequent one.

One of the most influential applications of the anthropic principle and of nonpredictive logic has been made by Brandon Carter of Cambridge. Carter began exploring the anthropic line of investigation in "reaction against exaggerated subservience to the Copernican principle." Carter argues that although Copernicus demonstrated we must not "assume gratuitously that we occupy a central position in the universe," it does not follow that the situation of human observers cannot be privileged in any way. The position of the observer is necessarily special at least to the extent that certain conditions (of temperature, chemical environment and so on) are prerequisites of his existence. "What we can expect to observe," Carter notes, "must be restricted by the conditions necessary for our presence as observers," and so "although our situation is not necessarily central, it is inevitably privileged to some extent."

Carter's discussion of the anthropic principle represents an interesting conjunction of the physics of the very large and the very small; to illuminate cosmology he relies on an unusual explication of quantum mechanics called the many-worlds interpretation. The many-worlds interpretation was proposed by
Hugh Everett III of Princeton and w
developed further by Bryce S. DeW
and John Archibald Wheeler of the U
versity of Texas at Austin. In the qua
tum theory predictions give only t
probability of an event and not a dete
ministic statement of whether or not t
event will take place. For example, t
trajectory of an elementary particle
described by a wave function, a mat
ematical expression whose amplitu
varies in both space and time. The pro
ability of finding the particle at a giv
point is the square of the amplitude
the wave function at that point. If
observation is actually made at t
point, however, the particle is eith
found there or not found there. A ce
tral philosophical concern in quantu
mechanics is reconciling the probab
listic interpretation of the wave fun
tion with the deterministic outcome
observations. When the particle is o
served at a certain position, did it ha
that position all along, even before t
observation was made? If it did, it is n
clear how to interpret the other poin
in space to which the wave function a
signed a nonzero probability.

The many-worlds interpretation
quantum mechanics asserts there is
fundamental difference between the o
served position of the particle and t
other points to which the wave functi
assigned a nonzero probability. The pa
ticle exists at all the points. In order f
this to be true, however, it is necessa
to suppose there are infinitely man
worlds, in each one of which the partic
has a definite position. What happe
during a measurement is that one wor
is selected from among the infinite ran
of possibilities. The wave function
still-important because it continues
describe the totality of the worlds.

Although the many-worlds interpr
tation may seem bizarre, it cann
be ruled out on the basis of the physic
evidence; it is compatible with the r
sults of all experiments. The interpret
tion has the virtue of reconciling t
continuity of the quantum-mechanic
wave function with the discontinuity
the process of measurement.

The concept of other worlds did n
originate with Everett. Some three ce
turies ago Gottfried Wilhelm von Lei
niz proposed that there are infinite
many possible worlds, each one inte
nally consistent and having its own cha
acter. Some of the worlds would be vas
ly different from the actual world, wit
unfamiliar initial conditions, fundame
tal constants and laws of physics; oth
worlds would differ from the known on
only in subtleties. For example, the
would be a world identical with our ow
except that its Julius Caesar did n
cross the Rubicon. In another world th
difference would be that Judas did n
betray Christ. The one constraint on

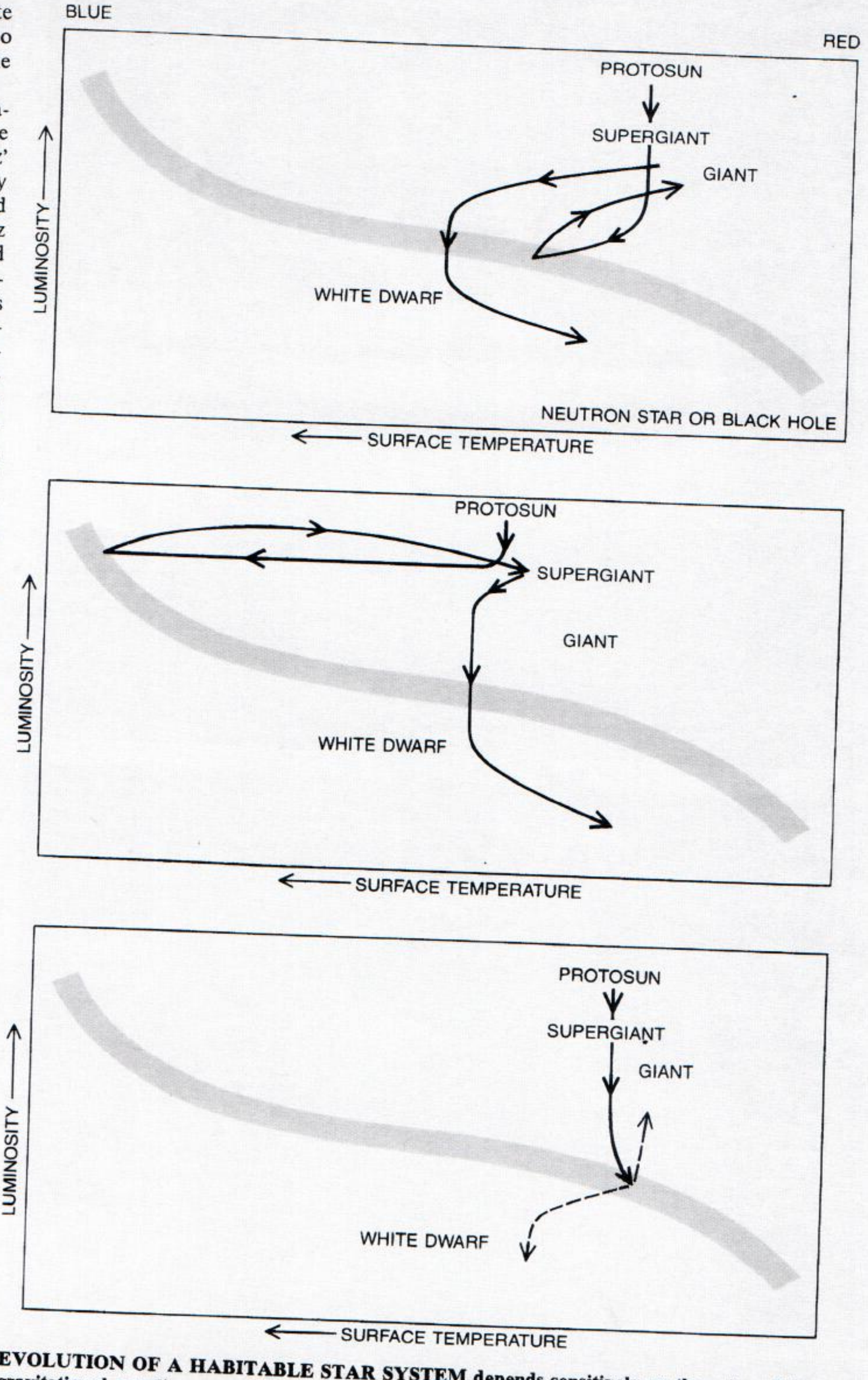
possible world is that it cannot violate the law of noncontradiction: there is no world in which Caesar both crossed the Rubicon and did not cross it.

In Everett's many-worlds interpretation of the quantum theory all the worlds are equally real. In Leibniz' view, on the other hand, there is a reality principle that singles out a real world among all the possible ones. Leibniz thought scientific investigation would reveal that the observed world maximizes a property he called at various times "economy," "perfection" and "optimality." The last term is the most revealing. Leibniz explained that the optimal world exhibits the richest variety of phenomena possible under the physical laws that describe the phenomena. He employed the concept of optimality to explain the laws of reflection and refraction in optics, and the concept inspired him to develop the principle of the conservation of energy.

In combining the anthropic principle with the many-worlds interpretation of quantum mechanics, Carter also introduces a reality principle. The complex property that distinguishes the real world is not Leibniz' idea of optimality but a property I shall call life-support- veness. From Everett's infinite ensemble of worlds Carter considers as real only those worlds satisfying a biological requirement: they must include features hat make possible "the existence of any organism describable as an observer."

Carter relies on this idea to explain the weakness of gravitation. According to the many-worlds interpre- ation, worlds might exist in which the oupling constant takes on all possible values from very weak to very strong. The anthropic principle can then explain why we live in a world where the onstant has the observed value. Carter emonstrates that if the coupling con- tant were much different, planets either would not have formed or would not ave survived long enough for intelli- ent life to evolve. Because an observer resumably requires a planet to inhabit, he existence of an observer is strongly nked to the value of the constant.

Carter's demonstration is based on an nteresting property of the stars called ain-sequence stars, which include the un. Such stars are at a stable stage of volution in which the energy liberated y thermonuclear fusion balances the orce of gravitational attraction. They re designated main-sequence stars be- ause in a Hertzsprung-Russell diagram a graph of luminosity v. surface temerature) they fall in evolutionary se- uence in a narrow band. Most proper- es of stars do not depend sensitively on e value of the gravitational coupling nstant. An exception is the sharp divi- on of the main-sequence stars into blue ants (hot, bright, massive stars) and



EVOLUTION OF A HABITABLE STAR SYSTEM depends sensitively on the value of the gravitational coupling constant. In these Hertzsprung-Russell diagrams the diagonal band is the main sequence, where stars in a stable stage of evolution are arranged in sequence. The top diagram shows the evolution of the sun in the actual universe. The gas and dust of the protosolar cloud collapsed under the influence of their own gravitation to form the sun, a star on the main sequence. The collapse took roughly 10 million years. After 10 or 15 billion years on the main sequence the sun will explode and become a red giant. Shortly thereafter it will evolve into a white dwarf and then slowly burn out. The middle diagram shows the evolution of the sun in a universe where the gravitational coupling constant is an order of magnitude larger. The sun spends little time on the main sequence but quickly evolves into a blue giant. The right half of the main sequence includes virtually no stars. The bottom diagram shows the evolution of the sun in a universe where the gravitational coupling constant is an order of magnitude smaller. The protosun enters the main sequence as a red dwarf, which remains on the main sequence for an extremely long time but radiates little energy. The left half of the main sequence includes few stars. Neither a blue giant nor a red dwarf could sustain life; the blue giant dies too soon and the red dwarf radiates too weakly. The anthropic principle asserts that the presence of life on the earth explains why the sun is at the division between the blue giants and the red dwarfs and hence why the gravitational constant has the value it is observed to have.

ALTERNATIVE WORLDS are suggested by two drawings based on an engraving by Gustave Doré. In one world Judas betrays Christ with a kiss; in the other world Christ is not betrayed. This example was cited by Gottfried Wilhelm von Leibniz some three centuries ago when he proposed that there are an infinite number of possible worlds, each one internally consistent. Some of the worlds would have laws of physics, fundamental constants and initial conditions vastly different from those in the observed world. Leibniz thought the observed world is distinguished from other possible worlds by its having the richest variety of phenomena possible under the physical laws that describe the phenomena. The anthropic principle is often linked to a version of the idea of alternative worlds. For a world to be observable it must satisfy a biological requirement: it must include features congenial to the emergence of life.

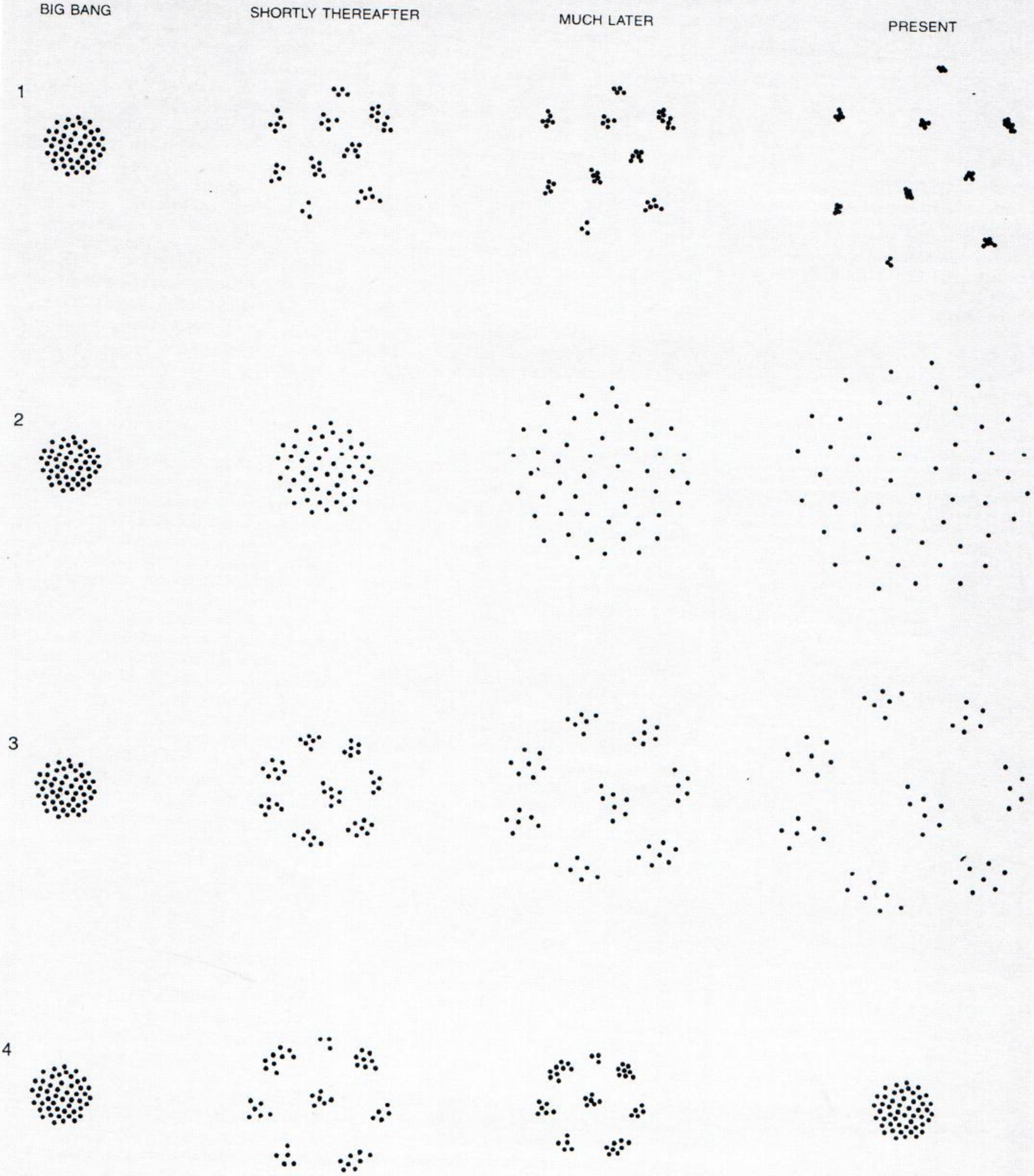
red dwarfs (cool, faint, compact stars). The luminosity of a star is proportional to the fourth power of its mass, and so a blue giant rapidly converts its substance into energy; it has a short lifetime. A red dwarf gives off comparatively little energy and lives much longer.

The emergence of life demands two things of a star. First, it must live long enough for living organisms to evolve. Second, it must radiate enough energy to warm a habitable region of space, that is, a region where a planet could have a stable orbit. Neither a blue giant nor a red dwarf satisfies both conditions; the blue giant burns out too quickly and the red dwarf radiates too feebly. What is needed is a star such as the sun, whose position on the main sequence is at the sharp division between the blue giants and the red dwarfs; only a star of this kind has a suitable combination of lifetime and radiant power. If the gravitational coupling constant were an order of magnitude larger, the main sequence would consist entirely of blue giants. If the constant were an order of magnitude smaller, the main sequence would consist only of red dwarfs. In either case life-supporting stars would not exist.

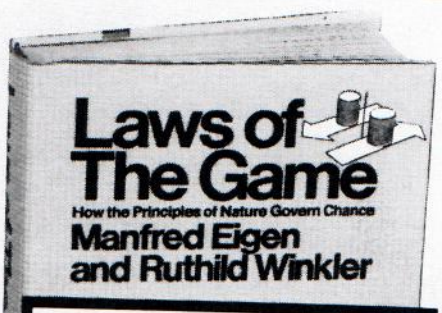
As Carter acknowledged, his argument is rather speculative. The formation of planets is not yet understood well enough to rule out completely the possibility that habitable planets would form in a universe with a different gravitational coupling constant. It must be noted, however, that this uncertainty is related not to the logic of the argument but to its empirical premises.

Carter has relied on the anthropic principle in other contexts, which are based on sounder empirical premises. For example, he has observed that the coupling constant associated with the strong, or nuclear, force "is only marginally strong enough to bind [protons and neutrons] into nuclei; if it were rather weaker, hydrogen would be the only element, and this too would presumably be incompatible with the existence of life."

Collins and Hawking were also led to invoke the anthropic principle. Their investigation set out to account for two observations: the large-scale isotropy of the universe, and particularly of the microwave background radiation, and the presence of smaller-scale inhomogeneities, such as galaxies. They found that the crucial factors are the initial recessional velocity of the matter created in the big bang and the escape velocity of the matter (the speed it would need to overcome its gravitational attraction). If the recessional velocity is less than the escape velocity, the universe collapses before isotropy can develop. If the recessional velocity is greater than the escape velocity, galaxies and other clusterings of matter cannot develop unless there are small-scale



MODELS OF COSMIC EVOLUTION indicate that the present universe, characterized both by large-scale isotropy and by smaller-scale inhomogeneities such as galaxies, would not have arisen if the recessional velocity of the matter formed in the big bang were not equal to the escape velocity of the matter (the speed it needs to counteract its gravitational attraction). The first row of drawings shows the actual evolution of the universe. The big bang had arbitrary, small-scale perturbations, which developed into inhomogeneities that condensed into galaxies. The second row shows the evolution of a universe in which the recessional velocity is greater than the escape velocity and the big bang is homogeneous. The present universe would be completely homogeneous and thus would have no galaxies. The situation would be no better in such a universe if the big bang had arbitrary, small-scale perturbations, as the third row indicates. Such perturbations would result in large-scale inhomogeneities that would not condense into galaxies. The fourth row presents the evolution of a universe where the recessional velocity is less than the escape velocity and the big bang has small-scale perturbations. The perturbations grow into inhomogeneities that eventually start to condense. Before galaxies can form, however, the universe collapses. It appears that the observed combination of large-scale isotropy and small-scale clustering could arise only from highly specific initial conditions. C. B. Collins and Steven W. Hawking have proposed that the singularity of the observed universe can be understood by combining the anthropic principle with the idea of alternative worlds. From an ensemble of infinitely many universes having all possible ratios of recessional velocity to escape velocity, the only universe in which life could emerge is the actual universe, where the velocities are equal.



inhomogeneities in the initial distribution of matter at the time of the big bang. Such inhomogeneities, however, would have resulted in large-scale anisotropy in the present universe. Collins and Hawking reluctantly concluded that the observed combination of large-scale isotropy and small-scale clustering can result only if the recessional velocity is exactly equal to the escape velocity. Hence the observed universe is a highly privileged one indeed, where the recessional velocity has one arbitrary value out of an infinite range of possibilities.

Collins and Hawking suggested that the discomforting singularity of the observed universe could be understood through the anthropic principle. They began by postulating an ensemble of infinitely many universes having all possible initial conditions, including all values of the recessional velocity. In almost all these universes matter could not condense into galaxies. The only universe in which matter could both form galaxies and exhibit large-scale isotropy is a universe whose recessional velocity is equal to the escape velocity. Collins and Hawking conclude that since "the existence of galaxies would seem to be a necessary precondition for the development of any form of intelligent life,... the fact that we have observed the universe to be isotropic is therefore only a consequence of our existence."

What does the anthropic principle suggest about the overall structure of the world? Suppose in the years to come the anthropic line of investigation reveals that even the smallest change in any initial condition of the universe or in the value of any fundamental quantity would not have allowed life to evolve. This would suggest that of all possible worlds the actual world is the only one congenial to life. Much more evidence would be needed, however, before such a conclusion could be advanced with any confidence.

Wheeler has addressed a still grander question: "How did the universe come into being?" Most philosophers of science deny that the question is scientifically meaningful; any answer would seem to call for a frame of reference beyond science because the very fabric of science (namely space-time) and the laws of physics that describe space-time emerged when the universe was created in the big bang. Wheeler nonetheless argues that as long as one lacks firm evidence of the meaninglessness or undecidability of the question, one cannot be content "to let a major question remain forever in the air, the football of endless indecisive games."

Wheeler approaches the question by analyzing the logic of explanations adopted in physical theories since the Scientific Revolution of the 18th century. He maintains that the logic consists in reducing a phenomenon to a more fundamental one. Thus the concept of valence in chemistry was reduced to the electrical properties of atoms and the temperature of a gas was reduced to the movement of atoms and molecules. It seems the logic of reduction can have only two possible outcomes, both of which Wheeler finds untenable. Physical theory could terminate in some fundamental, indivisible object or field; alternatively reduction could reveal layer on layer of structure ad infinitum.

Wheeler's way of escaping this quandary is to propose that the reductive mode of logic may itself come to an end. "One finds himself in desperation asking if the structure, rather than terminating in some smallest object or in some most basic field, or going on and on, does not lead in the end to the observer himself in some kind of closed circuit of interdependences." His argument draws on the connection established in quantum mechanics between the observer and the quantum phenomenon he observes. The many-worlds interpretation of quantum mechanics minimizes the role of the observer because the world he observes is considered to be no more real than any other world. Commoner interpretations of quantum mechanics, however, define reality as that which is observed; the observer contributes to reality by the very act of observation. Wheeler adopts an extreme version of this idea by proposing that for a universe to be real it must evolve in such a way that observers come into existence.

In support of this position Wheeler cites the anthropic principle. He contends that "no reason has ever offered itself why certain of the constants and initial conditions have the values they do, except that otherwise anything like observership as we know it would be impossible." He wonders whether one could not "envisage as Carter does 'an ensemble of universes' in only a very small fraction of which life and consciousness are possible? Or ask as we do now if no universe at all could come into being unless it were guaranteed to produce life, consciousness and observership somewhere and for some little length of time in its history-to-be?" Wheeler rejects the common view that life and observership are only accidents in a universe independent of observers and argues instead that "quantum mechanics has led us to take seriously and explore the directly opposite view that the observer is as essential to the creation of the universe as the universe is to the creation of the observer."

With this hypothesis Wheeler has carried the anthropic principle far beyond the domain of the logic of explanation; he has crossed the threshold of metaphysics. Few scientists or philosophers of science would be comfortable with his vision. It remains to be seen whether the less grandiose applications of the anthropic principle will win acceptance.