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Frontispiece, FIG. 1. The Crab Nebula. Distance: 3000 to 5000 light years.

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OUR UNIVERSE: THE KNOWN AND THE UNKNOWN*

By JOHN ARCHIBALD WHEELER

WHAT KIND of a universe do we live in? A strange one, yes. But where does the strangeness mostly lie? In the seen? Or in the unseen? Shall we fix our attention on the billiard balls as they now bat about the billiard table? Or shall we ask how the game began, and how it will end?

Who will not choose first to look about a little at the game? If then deeper questions come to mind, who will stop our asking them?

Our universe is incomparably more interesting than any play at billiards. The formation of new stars and the explosion of old stars and the greatest variety of events, gigantic in scale and in energy, outrival the most gorgeous fireworks explosion that anyone could imagine in his wildest dreams.

A Famous Supernova

Take up the telescope and turn it on the Crab Nebula. There was no Crab Nebula a thousand years ago. At that time astronomy was at a low level in Europe. Not so in China. There astronomers regularly swept the skies and recorded their observations. In July 1054 they reported a new star. It grew in brightness from day to day. In a few days it outshone every star in the firmament. Then it sank in brilliance, falling off in intensity from week to week. At each date the nova, or supernova as we more appropriately call it, could be compared with neighbor stars for brightness. Out of these comparisons by our Chinese colleagues of long ago one has today constructed a light curve. This light curve is similar to the light curve for supernova events which, through a powerful telescope, one sees from time to time today in far away galaxies. Only the great number of

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galaxies within telescopic reach has made it possible to observe as many of these events as one has seen today, for in an individual galaxy such as our Milky Way these events may be separated one from another on the average by as much as three hundred years.

Is there anything in the universe more spectacular than a supernova? The so-called quasistellar sources, or quasars, discovered in 1963 are more brilliant; but they also lie at far greater distances and are far more difficult to study. Moreover, many investigators believe that a quasar is not different in character from a supernova except in this, that it consists of many supernovae, exploding one after another with sufficient frequency to provide a more or less regular source of light. Thus, there is no convincing evidence that there is anything more impressive in the universe in the way of a single dramatic process than a supernova explosion. What then can one learn from a supernova about the strange things that go on in the universe?

Of the debris from all the supernova events that have ever been seen, none has been studied in more detail than that from the explosion of July 1054. It forms an expanding luminous cloud, the Crab Nebula (Frontispiece, Fig. 1), the boundary of which today, nine hundred years after the event, has moved out about three light years from the point of explosion. The pattern of intensity is not uniform, and for a good reason. An octopus inhabits the nebula, an octopus whose twisting, waving arms are bundles of magnetic lines of force. Centered on these magnetic lines of force, electrons move in circular and spiral tracks. The energies of these electrons exceed by many powers of ten the highest energy from any accelerator ever built or ever projected. A captive electron as it rounds its circle, first on one side of the magnetic line of force and then on the other, over and over again, does what any electron does that is driven up and down a radio broadcasting antenna over and over again at high frequency. It radiates electromagnetic energy. The electrons of the Crab Nebula radiate X-rays, visible light, and radio waves. By observing the pattern of brightness of this radiation, its absolute intensity, its spectral composition and its direction of polarization, and studying these measurements, many investigators spread among several countries have managed to unravel for us the anatomy of the arms of the octopus, the general features of the magnetic lines of force and the electron orbits, and much more besides, including the stupendous total energy set free, of the order of 10^{49} ergs.

A supernova event is clearly explosive in character. A star explodes and drives matter off into space. But what about the observed magnetic field? Its source is not far to seek: in the original star itself. There is no star that one has been able to study in any detail which does not have a magnetic field associated with it. Moreover, magnetic lines of force imbedded in ionized matter have no choice but to follow along with that matter in its motion from place to place, as a linked line of policemen is carried along in a milling mob, an originally straight line growing ever more contorted as it goes. The matter thus influences the field; but the field also influences the matter. This dynamic coupling is under active investigation in at least two centers today. To date, no one has analyzed all the hydrodynamic turmoil that can go on in nine hundred years with sufficient detail to explain the structure of the octopus and his present rate of writhing. If it is difficult to account for this structure, it is because turbulence is a difficult science and hydromagnetic turbulence is a particularly difficult branch of that science.

The aftermath of the explosion thus presents complications—inessential complications, so far as we can judge, but still complications. What about the explosion itself?

Gravitational Collapse

It is the general belief that a supernova event is triggered by the straightforward astrophysical evolution of a star which has several times the mass of the sun and which is already compacted to a density a million times or more greater than the density of the sun. With further evolution it becomes still denser. A one per cent decrease in all dimensions brings about a two per cent increase in all gravitational forces, by reason of Newton's inverse square law of gravitation. Thus, increasing compaction implies increasing importance for the Newtonian forces. Ultimately, the forces of gravitation overwhelm the forces resisting compression. The star commences to collapse, at first slowly, then more and more rapidly. In a predicted time of less than one tenth of a second, the collapse of the core has run its course and energy has been imparted to the outer portions of the star which is still animating the octopus-like cloud of debris nine hundred years later.

What gives one any right to think that he can work out the story of the collapse with any reliability? It is one thing to analyze a star as nearly static as the sun. Is it not quite another matter to forecast the fantastic dynamics of a supernova? We know how to predict in much detail the nuclear reactions that go on in the sun and other stars, and the output of radiative energy from the surface. Can we speak with equal confidence about a star undergoing violent internal motion?

A bit of star was first brought down to earth at Alamogordo, N.M., in the first bomb test at 5:30 A.M. on July 16, 1945. No event in history ever gave a more dramatic example of man's understanding of how nature works. By one-shot design, without trial and error, one had achieved on earth temperatures larger by powers of ten than any seen before, temperatures that rivaled the center of the sun. A calculated device had generated a calculated pressure pulse more powerful by far than any push that ever before took place on the earth or in its interior. Events unbelievably different from anything in all past human experience were predicted, and predicted correctly.

Today, at the Lawrence Radiation Laboratory of the University of California at Livermore, Calif., there stands an impressive electronic computer. It predicts the performance of fission and fusion bombs far more complex than the Alamogordo device. Stirling Colgate, Michael May, and Richard White used it in 1964 and have used it more recently to predict the hydrodynamics of a supernova. Other investigators have since made calculations confirming and extending the Livermore picture of what goes on. The computer puts out a kind of moving picture record of events in the star which, like events within the bomb, are beyond the power of direct inspection.

The star lends itself to simple and reliable analysis because it has spherical symmetry—a feature also of the simplest imaginable bomb. If, in the one case, the assembly of the material is brought about by the pressure of high explosive applied to the outside, and in the other case by the attraction of gravity exerted from the inside, this is a difference of little consequence for the computing machines and for those who program them. Nor is it of any moment that human countdown determines the time when the pressure is applied to the outside of the nuclear device while the slow course of astrophysical evolution and stellar contraction determines the time when gravitational attraction gets the upper hand within the star. The laws governing the conversion of force into motion are the same in both cases. The formulae for the flow of radiation are similar. The principles of nuclear physics are the same. No wonder, then, that workers in this field have predicted with considerable confidence many of the features of supernovae.

In the beginning, the material of the star collectively moves closer together at an ever increasing rate. Soon the core outstrips the outer portions of the star in the speed of its collapse. To this shrinking core increasing gravity imparts a more and more powerful squeeze. The material of the core, through being suddenly tightly compacted, is also heated to an enormous temperature.

Continued Collapse versus Collapse to a Neutron Star

Two very different fates befall the superdense core according as it is more massive than a certain critical figure, roughly comparable to the mass of the sun, or less massive.

A core less massive than the critical limit is stopped in its collapse by the onset of nuclear forces. They succeed in offsetting the pull of gravity, but only when the core has been squeezed to a condition comparable to the atomic nucleus itself in its density. This density is a million times or more as great as the density of the original star, even though that density was itself a million times or more in excess of the density of the sun—or the density of water. This hot core, this ten or a hundred kilometer sphere of nuclear matter, this giant nucleus, this encapsulated neutron star, by reason of its extraordinary temperature and its output of radiations, acts like a dynamite charge at the center of the enormously more extended remainder of the star. The sudden punch of this dynamite stops the infall of the envelope. It does more. It drives the envelope off at ever increasing speed. Seen in retrospect, the star presents us with a striking picture: first calm, then slow infall everywhere, then rapid implosion of the core, a stop with a shock, and finally explosion of the envelope.

Each layer of the envelope finds other layers in its way to impede its outward flight. The less such impedance a layer experiences the higher is the speed that it attains. The very outermost fraction of the envelope, the most exposed one hundred thousandth of the mass, is propelled to velocities very little less than the speed of light. So highly energetic does this layer become that the individual atomic nuclei break loose from all constraints. Each begins a long travel of its own through space. Along this line, Colgate and Johnson, and Ono, Sakashita, and Ohyama have proposed to account for the production of the cosmic rays that course about our galaxy. Subsequently, Colgate and White and other workers have found that this supernova acceleration mechanism gives a reasonable account not only for the observed spectral distribution in energy of the cosmic ray particles, but also for the order of magnitude of the absolute intensity. Fascinating connection between the world of stars and the world of particles!

In a star where the mass of the core exceeds the critical mass, then the collapse of the core under ever stronger gravitational forces is not halted as nuclear densities are reached. The matter of the core pours torrentially inward from all directions like a thousand Niagara Falls on its way down from the original dimensions to ever smaller sizes. Slow it does a little when it reaches the density of nuclear matter, as an express train lets up speed a trifle in roaring through a town, but then the speed goes higher and higher. In less than a tenth of a second the collapse is complete. No core is left to serve as a dynamite charge at the center of the star. No punch arises to drive out into space the remainder of the star. In that envelope a weak thermonuclear reaction may at most briefly flicker, and at most drive off a minor amount of matter. No supernova flares up, according to the calculations made to date by two groups of workers.

Two kinds of collapse we are thus driven to expect in stars which have slowly developed in the course of time to an overdense state. In one type of event, where the core exceeds the critical mass, the collapse goes to completion, and little if anything is seen. In the other kind of collapse, the core, endowed with a less than critical mass, ends as a neutron star; and we see a supernova.

What right have we to talk of complete collapse? What do we know about the behavior of matter at densities above nuclear density that lets us say there is not some further stopping point on the way toward complete collapse? Not much, but this much: there is an upper limit to the rigidity of matter. The higher the rigidity of matter, the greater the speed of sound. The maximum rigidity gives a speed of sound equal to the speed of light. No higher rigidity is permissible. Else the speed of sound would exceed the speed of light and a thoroughly tested principle of special relativity would be violated. However, the critical elasticity simply is not enough to stop the collapse.

Collapse is inevitable, so the prediction reads. Into that prediction enters not only a principle about the upper limit to the elasticity of matter but also Einstein's theory of how gravitation acts under extreme conditions. What right do we have to assume that Einstein's great standard 1915 geometrical theory of gravitation, his "geometrodynamics," makes sense under these conditions?

Collapse of a Star as Related to the Expansion and Recontraction of the Universe

No test of Einstein's theory is more dramatic than the expansion of the universe itself, and none has a closer bearing on the phenomenon of collapse. Three other tests of relativity are better known: the precession of the perihelion of Mercury around the sun, the bending of light by the sun, and the redshift of spectral lines by the gravitational pull of the sun. The recognition of the fourth effect came in 1922, not from Einstein himself but from Friedmann, whose predictions in the beginning Einstein even questioned: a closed universe of roughly uniform density will inevitably expand, reach a maximum dimension, and recontract, ending up with a final complete gravitational collapse as swift and complete as the tininess and swiftness of the expansion at its start. In contrast, Einstein had always believed the universe will remain forever at its present size, and so had all the world. Einstein could not believe Friedmann's predictions though they came straight out of his own theory. Finding no escape from the calculations and unwilling to accept a conclusion so out of keeping with all expectation, Einstein reluctantly and uncertainly looked for a way to change his otherwise compelling theory and introduced into it a so-called cosmological term. Only in this way did he see any possibility to have a universe static and in accord with what he thought experience taught. Five years later Hubble found that the universe is expanding. Einstein thereafter renounced the cosmological term saying that it was the "worst blunder of his life." If Einstein had held fast to the original theory, Hubble's discovery could hardly have been regarded as any but the most dramatic test of geometrodynamics.

What possible meaning does it have to talk about the expansion of the universe? If everything expands alike—the universe, the galaxies, and all

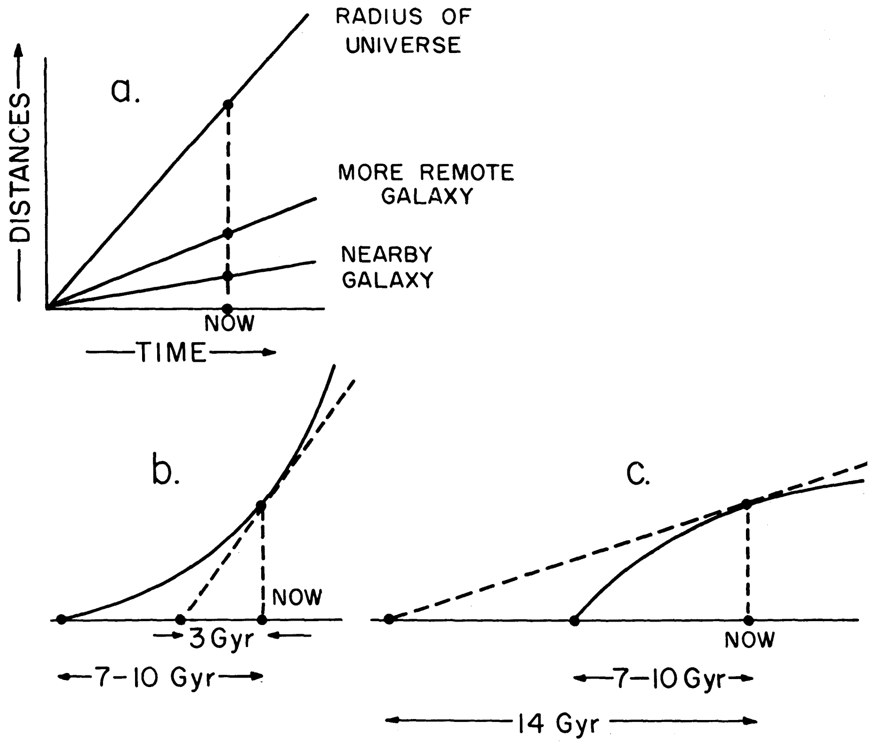

FIG. 2. Expansion of space. (a) Uniform expansion at a rate that remains constant in time. All distances have half their present values at a common time back in the past. All distances extrapolate back to zero at a still earlier but still common time. Thus a single one of these distances—for example, the radius of the universe—is an adequate indicator of how all the others vary with time. (b) Expansion at an accelerating rate; radius of the universe as a function of time. The actual time back to the start of expansion (roughly 7 to 10 × 10^9 years; estimated from calculated ages of individual stars and star clusters) exceeded in the 1930's the time estimated from the present rate of expansion of space (dashed line drawn tangent to curve; extrapolates back to zero at a "Hubble time" of about 3 × 10^9 years). Such an accelerated rate of expansion violated Einstein's standard 1915 relativity theory and led to theories of "the continuous creation of matter." (c) New figure for "Hubble time" or extrapolated time back to start of expansion (dashed line; 14 × 10^9 years) differs from figure for same quantity in the 1930's because of drastic correction in scale of astrophysical distances that took place in intervening time. Fact that this time exceeds actual time since start of expansion (roughly 7 to 10 × 10^9 years) indicates that expansion is proceeding at a decelerating rate, in contradiction to "theory of continuous creation" and in accord with Einstein's theory (effect of gravitational forces between parts in slowing down expansion of whole).

our meter sticks—then who is to say that any expansion at all has taken place? However, meter sticks do not expand. The radius of the earth's orbit does not change. The size of the galaxy does not increase. These standards of measurement remain fixed. What increases is the separation from one galaxy to another. Who has not seen in his mind's eye a model for this expansion? Onto the surface of a partly inflated rubber balloon we have glued here and there a penny. We inflate the balloon. No penny changes its size. The distance between pennies increases. From a given penny the distance to a neighbor penny increases at a certain rate (Fig. 2*a*), and the distance to a penny twice as far away increases twice as fast. Each penny thinks itself the center of an expanding cloud of pennies. All are right—because the balloon itself is expanding.

If prediction, then great doubt, and then confirmation was the first cycle in the strange history of geometrodynamic cosmology, it was not the last. Einstein's theory predicted that the galaxies, like a thousand rocks thrown out in space, should recede from each other—but recede more slowly as time goes on because of the gravitational attraction between one and another—and eventually stop their outward flight and fall back together, at first slowly and then more and more rapidly. On this basis the rate of the expansion of the universe today should be slower than it was some billions of years (Gyr) ago. In other words the actual time back to the start of the expansion ought to be shorter than the time as one would deduce it (Hubble time) from the present rate of expansion (Fig. 2*c*). In contrast the observations as they came in indicated (Fig. 2*b*) the opposite. Many workers grappled with this difficulty in the 1930's and more than one lost faith for a time in Einstein's theory. This was the era of theories of "continuous creation of matter" and later the era of "the continuous creation of theories." Later it turned out that an error had been made in the basic astrophysical standard of length employed in estimating the remoteness of distant galaxies. Thus, the distances were wrong but the velocities of recession, being based upon observed redshifts, were right, and consequently the old figure of three and one half billion years back to the start of expansion, based on the then currently believed figures, was also wrong. No longer can one point to any discrepancy between the predicted and observed rate of expansion. And between this predicted and observed expansion and the recontraction of the universe or the gravitational collapse of a star there is not one significant difference of principle.

The Black Hole

If gravitational collapse is as inescapable in a star as geometrodynamics is inescapable in the universe, then what would be the appearance of the collapsing core if it could be seen from afar without the interference of the supervening envelope? The hot core material is brilliant and at first it shines strongly into the telescope of the observer. However, by reason of its faster and faster infall it moves away from the observer more and more rapidly. The light is shifted to the red. It becomes dimmer millisecond by millisecond, and in less than a second too dark to see. What was once the core of a star is no longer visible. The core like the Cheshire cat fades from view. One leaves behind only its grin, the other, only its gravitational attraction. Gravitational attraction, yes; light, no. No more than light do any particles emerge. Moreover, light and particles incident from outside emerge and go down the black hole only to add to its mass and increase its gravitational attraction. Has the black hole a size? In one way, yes; in another way, no. There is nothing to look at. One could of course imagine thrusting a meter stick toward the center of attraction until it "touched base." However the powerful tidal forces will tear apart that object and every other object. No conventional measurement of the dimensions is possible. Even to speak about the dimensions of the object in any conventional sense is out of the question. However a light ray can be shot at the black hole, not straight on, but directed far enough off center to one side or the other just barely to escape capture down the black hole—to emerge eventually into a faraway detector of photons. The "diameter" of the black hole as defined in this way is of the order of 10 km, the precise value depending on the mass of the core that underwent collapse. These are the long-known predictions of standard long-established theory.

What hope is there to observe a black hole? Or the neutron star from the incomplete collapse of a less massive core? The complete blackness of the one and the low candle power expected for the other make the search for either kind of object, in isolation, almost hopeless. Try as many have, no one has detected with a telescope anything near the center of the Crab Nebula that can be identified with a residual core from that supernova explosion. Happily, isolation is not the universal condition for every star. Many have companions and often the companion is invisible. Its presence is revealed only by the to and fro motion of the visible component every so and so many hours, or every so and so many years. The amplitude of the motion and the mass of the visible component are enough to permit estimates of the mass of the invisible object. Sometimes it is only of planetary order. In other cases the mass is comparable to the mass of the sun itself, and could be compatible with interpretation as a black hole or as a neutron star. In neither case will one expect any detectable drop in the intensity of the bright component as the collapsed core sweeps across its disc. Mercury, 5000 km across, causes no detectable dimming as it crosses the sun; and the effective diameter of a black hole or a neutron star is 100 or 1000 times smaller. Schklovsky has pointed out that many visible stars eject matter and that some of this matter, falling on a neutron star, will hit with such an impact as to generate X-rays in substantial quantity. Consequently, Goebel and others are now looking for correlations between X-ray sources and binaries in which one component is invisible. To find such a correlation would be one thing. To test whether the X-ray source varies in time with the period of the binary will be much more difficult. An X-ray detector shot up from earth remains above the atmosphere only 5 minutes.

The Missing Matter

One can look for the effects of an individual black hole. One can also ask about the gravitational influence of large numbers of black holes spread about through space.

If in the confrontation between Einstein's geometrodynamics and observed cosmology we have been through two cycles of prediction, doubt, and confirmation, are we entering a third? If his theory is correct and his further arguments are valid that the universe is closed and roughly spherical, then not only will the universe reach a maximum dimension and recontract, but in addition, enough matter must now be present in the universe so that by its gravitational attraction it will be able to slow down the present expansion and bring it to a stop. The predicted density of matter exceeds by a factor between 10 and 100 the density that one is able to find in the dust and stars of galaxies—imagined to be ground up and distributed over all space. The "missing matter" is actively sought by several investigators. More than one investigator has proposed that ionized hydrogen in substantial quantities occupies the space between the galaxies. Quite another suggestion has been advanced by Novikov and Zel'dovich: that black holes scattered through space in appreciable numbers contribute substantially to the mass of the universe. It would be difficult to cite any topic in astrophysics more challenging to the investigator than the search for the missing matter!

It is not enough to look for improved means to detect black holes and neutron stars already in existence. One wishes in addition to get signals from the act of creation of new objects. Of all signals from gravitational collapse none is more characteristic than gravitational radiation. Any mass of unsymmetrical shape changing its configuration with time will give off gravitational radiation, as Einstein showed as long ago as 1918; but only in the gravitational collapse of a rotationally flattened star can one point to a mass large enough and speeds of change great enough to provide an obvious source of gravitational radiation.

Since 1966 Weber has had a detector of gravitational radiation in operation at College Park, Md. In more than a year he has detected more than ten events. Are they caused by gravitational radiation? One cannot yet say with certainty. Weber has emphasized more strongly than anyone how long the road is from detecting "events" to proving that pulses of gravitational radiation are falling on the earth; and how much farther still to establishing the source of such a pulse. The difficulties are formidable. Nevertheless, a promising start has been made with this new method to detect gravitational collapse.

Classical Prediction: Infinite Density in a Finite Time

A black hole and a normal star revolving around their center of gravity; black holes contributing a substantial part of the mass density of the universe; the formation of a black hole generating a pulse of gravitational radiation: all of these effects are external to the collapsing mass. Even more fascinating is what goes on inside it. The time scale inside is totally different from the time scale outside. According to general relativity, a standard clock far away outside and a standard clock located on the falling matter inside will keep time at quite different rates. As seen from outside the black hole will live for eons. But, to an observer who rides inward on a collapsing ball of matter, the density goes up faster and faster and in less than a second is predicted to go to infinity. A computer computing ahead from instant to instant the hydrodynamics of the collapse arrives at numbers so enormous that it has to stop. In effect smoke rises from the computer. With this prediction of an infinite density, classical theory has come to the end of the road. A prediction that is infinity is not a prediction. Something has gone wrong. Of all the topics discussed at the 1965 London International Conference on Gravitation Physics no topic attracted more interest than gravitational collapse. None was considered more important and on none was there more disagreement. The issue was simple. Will minor departures from sphericity save a collapsing system from being driven to infinite densities? A first tentative approach by Khalatnikov and Lifshitz suggested that infinite density—and infinite curvature of space—would be reached only in the case of perfect symmetry. However Penrose, Hawking, and Misner gave compelling arguments why minor departures from sphericity will not save the system from being driven to a singular state. Subsequent to the conference, Hawking, Penrose, and Geroch, working within the framework of Einstein's theory, giving up spherical symmetry and accepting one or another set of simple conditions on how the motion starts, have proved that a singular condition inevitably develops. Zel'dovich has arrived at the same conclusion in another way. It might have seemed an attractive picture to think of the matter in the star core, or the matter in the final stages of collapse of the universe itself, as shrinking down to a twisting turning writhing ball of matter of finite size—and going on from there to re-expansion. Not so. No one knows a cheap way out. The infinity is an infinity so long as one stays within the context of classical theory. Infinity is a signal that an important physical effect has been left out of account. The root of the new physics is not far to seek. It is the quantum of action.

Geometrodynamics and the Quantum

Einstein, who did so much to bring the quantum principle to fruition in his earlier years, disowned it in his later years. He who, along with

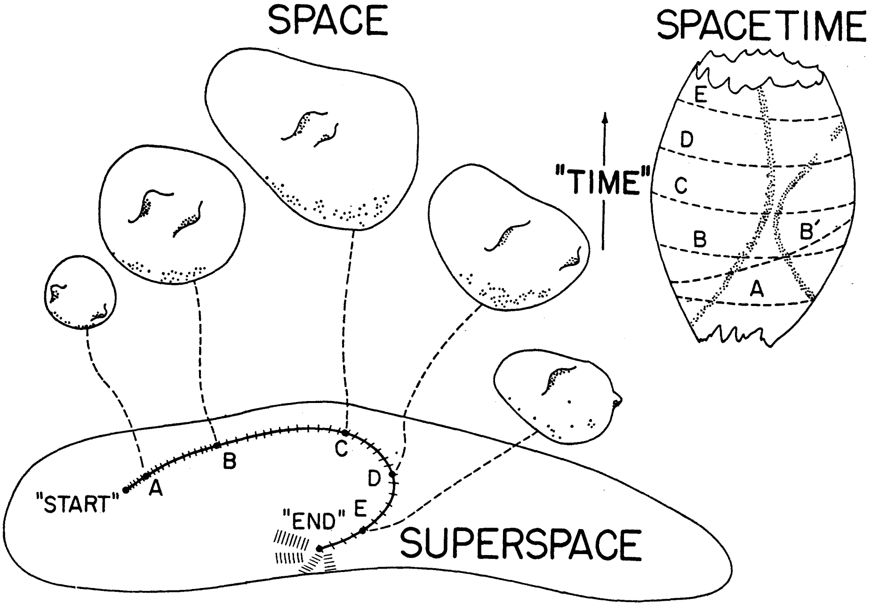

FIG. 3. Space, spacetime and superspace, depicted symbolically. Upper left: Five sample configurations (the 3-dimensional geometries A, B, C, D, E) attained by space in the course of its expansion and recontraction. The two lumps symbolize the curvature of space in the vicinity of two stars, other stars being omitted to simplify the diagrams. The two stars move through space as the space itself expands and recontracts. Space, actually 3-dimensional, is here drawn for convenience of representation as if 2-dimensional ("surface of potato"). Upper right: Spacetime, the classical history of space. A cut through spacetime, such as A, gives a momentary configuration of space.[*] Let the universe run through one conceivable dynamical history, the particular one indicated by this particular spacetime. This spacetime admits as spacelike slices, or as "yes" 3-geometries, all the 3-geometries A, B, C, D, E and many more besides, including for example a slice such as B′. However, slice as one will through the given spacetime, he will be unable to get most conceivable 3-geometries. They are therefore appropriately called "no" 3-geometries. The "yes" 3-geometries constitute a small subclass of the totality of all 3-geometries.[†] Below: Superspace, the arena within which space undergoes its dynamic evolution (actually infinite dimensional; depicted here as 2-dimensional). Each "point" in superspace (such as A) stands for an entire 3-dimensional geometry (also denoted by A; "potato" at upper left). The "yes" 3-geometries constitute a submanifold[‡] of superspace. In a classical dynamical history, space remains sharply confined to such a submanifold, and the history has a sharp beginning and a sharp end. Not so in the real world of quantum physics. There the dynamics is symbolized by a wave with a finite spread. A succession of wave crests shows in the diagram. The wave character of dynamics (1) brings about fluctuations in the geometry of space at small distances (2) prevents one from using such concepts as "spacetime," "time," "before" and "after" except in the approximation of classical physics (3) completely alters the character of the final stages of gravitational collapse and (4) brings about an inescapable coupling to other alternative histories of the universe (waves continuing past region of superspace marked "End").

[*] Spacetime is 4-dimensional, but is shown as 2-dimensional ("surface of egg") because of the limitations imposed by ink and paper. The same limitations force A, which is actually 3-dimensional, to be represented in this particular diagram as if 1-dimensional ("dashed curve running around egg"). The tracks of the two stars through spacetime show as two ridges ("world lines"; shaded in on "surface of egg").

[†] Given these "yes" 3-geometries, one has the wherewithal to reconstruct the entire spacetime, or 4-geometry. This spacetime is "rigid": it defines a definite time relationship

Rutherford and Soddy, was the first to bring the concept of transition probability into the world, ended up the only leading physicist who did not accept it. In his later years, he hoped somehow to extract the quantum principle out of relativity rather than add it onto relativity. It would be difficult to cite today any physicist agreeing with this view. On the contrary, the opposite view is the center of one of the most important developments in theoretical physics since 1950: the quantization of Einstein's general relativity or geometrodynamics—an enterprise on which important contributions have come from Anderson, Bergmann, Deser, DeWitt, Dirac, Feymann, Higgs, Leutwyler, Misner, Pirani, Rosenfeld, Schild, Schwinger, Weinberg, and many others. If the quantum principle and relativity are the two over-arching principles of twentieth-century physics, then the union of these two principles that we have today in "quantized general relativity" or "quantum geometrodynamics" is a body of knowledge of exceptional interest and nowhere more so than in the consideration of gravitational collapse. Appreciable as have been the difficulties in getting hold of the mathematics of quantum geometrodynamics, a simple conceptual difficulty cost us greater trouble in these years since Einstein's death. Relativity, by treating time as a fourth coordinate comparable in quality to the other three, had brought a great new unity into the description of nature. Einstein gave us spacetime in place of space. Nothing has been harder to learn than the necessity to go back from spacetime to space. Space is the dynamical entity which is the subject of discussion in geometrodynamics: three-dimensional space. Spacetime, with its four dimensions, is not the dynamical object. Spacetime provides the history of space as space changes with time (Fig. 3) but the object which does the changing is space.

Up until now one has always considered spacetime as the arena for physics. Every event, so one has come to think, past, present, or future, has its place in the great never-changing structure that we call spacetime. Classical geometrodynamics fits into spacetime and in no way more clearly so than this, that all the space-like slices through spacetime give one all the configurations that space can take on as it changes dynamically with time. Not so in quantum geometrodynamics. It bursts out of the bounds of spacetime. It claims a new arena for its own: superspace.

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between one event and another. One cannot define such time relationships nor even give any meaning to such terms as "before" and "after" when one deals with a random collection of 3-geometries. In contrast, the "yes" 3-geometries are distinguished by the fact that they *can* be reassembled into the particular 4-geometry or spacetime that happens to be illustrated.

‡ This submanifold of superspace is, like superspace itself, infinite dimensional, because there is an infinity of ways in which one "yes" 3-geometry can differ from another. However, the infinite number of the "yes" 3-geometries is of a lower order of infinity than the infinite number of all 3-geometries. Therefore, the collection of "yes" 3-geometries is indicated symbolically in the diagram by a domain of dimensionality only half of that which the draftsman has been able to allocate to superspace itself—this domain being the one dimensional smooth curve cutting across a two dimensional sheet of paper.

Superspace

Each "point" in superspace symbolizes and stands for an entire 3-dimensional geometry. Who that is accustomed to tell a potato of one shape from a potato of another will be surprised that one point in superspace can be distinguished from another?! One point, one "shape," or one "3-dimensional geometry"; another point, another shape. Millions of points, millions of shapes. What an enormous content superspace has, containing as it does every conceivable shape! Regarded in this wide domain of superspace, the classical history of space appears amazingly constricted. Only a narrow class of 3-dimensional geometries comes into evidence. They are the shapes that one finds by making in one way or another a spacelike slice through a particular spacetime (Fig. 3, upper right). If these are called "yes" 3-geometries, then "no" 3-geometries are infinitely more numerous. Space following the deterministic rules of classical geometrodynamics is infinitely careful where it treads in superspace!

Bolder is space following the principles of the real world of quantum physics. No longer does it distinguish between "yes" and "no" configurations. Instead, space recognizes a probability which may be great or small or intermediate in value for this, that, and the other 3-geometry.

Classical physics in effect marks out for space a narrow zone in superspace and says, "Stay here." And why? Because the shapes, the 3-geometries, the configurations that one encounters in this limited zone of superspace can be fitted together—somewhat as a child nests together his dozen colored boxes, one inside the other—to build up one single beautiful rigid classical structure, spacetime. Not so in quantum physics! No sharp yes or no rule there. Instead, one has a probability wave propagating in superspace (Fig. 3, superspace; ripples indicated symbolically). The track of this spread-out wave follows the yes-no rule of classical geometrodynamics in superspace no better than the great broad paintbrush of a bold painter follows the thin line of a pencil.

This "spread of the wave in superspace" has decisive consequences for the nature of time, for the character of space at small distances, and for the final phase of gravitational collapse.

Consequence one: the configurations of space which occur with appreciable probability are far more numerous than can be nested together and accommodated in any one spacetime. No longer is there any such thing as "the" spacetime manifold. And with spacetime gone, time is gone. The old means disappear to locate one event ahead in time or later in time than another. The words "before" and "after" lose their meaning. There is no well-defined significance to the question, "What happens next?" Only in a certain approximation, only if one does not look too closely, does it still make sense to employ such terms as "spacetime," "time," "before," and "after."

It is a second consequence of the way the probability wave spreads in superspace that the geometry of space at small distances is not well defined. Still less does space at small distances have the ideal smooth perfection envisaged by Euclid. Instead, it has a probability to have this, that, or the other geometry. In other words, space *fluctuates* between one configuration and another. These fluctuations in geometry are completely unobservable at the everyday scale of observations. Even at the scale of dimensions of atoms and nuclei they are totally negligible. Only when the scale of observation is still further narrowed do the fluctuations become appreciable. At the fantastically small scale of 10^{-33} cm—the so-called Planck length or critical distance—these fluctuations become all important. At these distances it is completely out of the question, according to quantum geometrodynamics, to conceive of space having the character of an ideal, God-given Euclidean perfection. Instead, the geometries of space which occur with appreciable probability differ drastically from one another, each also individually being as irregular as it could well be. Space is to be compared to nothing so much as a carpet of foam spread out upon the floor. The carpet of foam looks smooth to a casual glance. But closer inspection shows that it is made of millions of tiny bubbles, and a still closer view shows that the bubbles are continually bursting and new ones being formed. Such are the predictions!

No one can consider the new predictions of standard quantum geometrodynamics about fluctuations in the geometry of space without considering the old predictions of standard quantum electrodynamics about the fluctuations in the electric field. Present throughout empty space, these electric field fluctuations perturb the motion of every electron in every atom. They alter the otherwise expected energy of the electron. In all the inspiring history of physics since World War II there has been no greater triumph than to predict these effects—and to find and confirm them in microwave measurements of fantastic precision. How then can one doubt that the predicted fluctuations also take place in the geometry of space itself—surely with important consequences for the nature and the structure of elementary particles!

No "Next" at the "End" of the Universe

If there is no such thing as "the" geometry of space at small distances, then it is also true that there is no such thing as "the" universe at large distances. The wave that propagates in superspace bursts out of the narrow zone to which classical theory assigns the history of any "universe." One can state this effect in slightly different words: there is no unique history that one can ascribe to the universe. Instead, there is a certain probability of this, that, and the other history of the universe. Normally this probability aspect of the history, this inescapable quantum mechanical uncertainty, this indeterminism is quite inappreciable except when one concerns himself with what goes on at the Planck scale of distances.

However, in the initial phases of the universe as well as in the final phases of gravitational collapse of stars and gravitational collapse of the universe itself, the relevant physical dimensions are driven down to values comparable to the Planck length by the very physics of the collapse mechanism itself. Under these conditions, the phenomenon of indeterminism invades not merely the small scale geometry but dominates the entire collapse phenomenon itself. In the final phase of collapse, one history of the universe finds itself inescapably coupled with other, alternative histories of the universe (waves indicated in superspace in Fig. 3 near point marked "End"). To speak in these words is not to answer an old question about gravitational collapse, "What happens next?" The question, we now recognize, is devoid of content, and this for a simple reason: because the very words "before" and "after" and "next" have lost all meaning. The "new" histories of space which near "End" join onto, and are so strongly coupled to, the "old" history of the universe have no time correspondence whatsoever, one with the other. Quantum mechanical coupling by probability waves, yes; historical continuity, no. At this point of coupling any use of the word "time" in any normal sense of this word is completely out of the question.

The lack of historical continuity between one cycle of expansion and recontraction of the universe and another leads us to ask if the number of the elementary particles and their properties also differs between one such cycle and another. We are accustomed to the idea of fossil molecules and fossil atomic nuclei. Should we also accustom ourselves to the idea of fossil elementary particles? This piece of wood on which I lay my hand was made in a tree a few years ago from the carbon dioxide and water. Its molecules are "chemical fossils" of recent origin. The atomic nuclei of these carbon and oxygen atoms date back to an older epoch some billions of years ago, the time of thermonuclear combustion in the stars. They are "nuclear fossils." In another chemical environment the carbon dioxide and the water would have joined into a molecule quite different from cellulose. Nuclear matter cooked in a different star for a different length of time would have left us more iron and less oxygen as its fossil testament. Are we likewise to expect that the properties of the elementary particles and even their numbers differ between one cycle of the universe and another?

Is it more than mere talk to say that the phenomenon of gravitational collapse ties together the world of the very large and the world of the very small? Do the particles themselves bear living witness to this connection? Is any theory of the constitution of elementary particles doomed to incompleteness which does not recognize that one type of elementary particle has one mass in one cycle of the universe and another mass in another cycle? Eddington, Dirac, and Jordan long ago pointed out, and Dicke and Hayakawa have since stressed anew, the many signs there are in the so-called "large numbers" of a direct but mysterious connection between the world of the small and the world of the large. The characteristic dimension of an elementary particle exceeds the Planck length by a factor of 10^{20}. The estimated radius of the universe at the phase of maximum extension exceeds the characteristic dimension of an elementary particle by a factor of 10^{40}. The electric forces between two particles exceed the gravitational forces by a factor that is also 10^{40}. The estimated number of particles in the universe is of the order of 10^{80}. The four "large numbers" have evident correlations, one with another. Dirac has stressed that accident cannot have brought about such a simple connection between such enormous numbers. There must be a causal connection.

Dirac thought it natural to suppose that the large numbers change slowly with time during the evolution of the universe. In the intervening years, no generally accepted evidence has ever been found for any such change with time; and for the one of the four numbers easiest to measure there is increasingly precise indication that it does not change. The observed consistency of these large numbers, and the precision with which one of them is known to stay constant, together suggest that the particles keep their properties in any one cycle of the universe, faithful fossils from the fires of formation, constant throughout one cycle of the universe, but no more. Change with "time"? Incompatible with what we know. Change from one cycle of the universe to another? Conceivable. Compatible with what we know.

If there is no such thing as a "universal" value for the mass of an elementary particle—if the properties of a particle differ from one cycle of the universe to another—we will not be surprised. And surely someday—if Einstein's views of nature are correct—we will understand a particle, not as a foreign and mysterious interloper introduced from outside of space, but as an object "constructed out of space." We are as far today as anyone could well be from understanding the principles of construction. We can at most translate Einstein's vision into today's terms by speaking of the particle as a "quantum state of excitation of a dynamic geometry"; but how to calculate the quantum states of excitation of geometry is still beyond us. However, one thing we know: in discussing the dynamics of "empty" space, pure quantum geometrodynamics, we never encounter any length other than the Planck distance, 10^{-33} cm. Out of this number there is no way to construct a length of anything like the dimensions of an elementary particle except through multiplication by an enormous factor. There is no place in pure quantum geometrodynamics for such a factor to come from except from what we have long been accustomed to call "initial conditions"—the initial shape of space, and its initial speed of expansion, in this cycle of the universe. Here we find ourselves driven to new ground.

Initial Conditions: The Great Unknown

Never has physics come up with a way to tell with what initial conditions the universe was started off. On nothing is physics clearer than what is not physics: equation of motion, yes; initial position and velocity of the object which follows that equation of motion, no. Who does not remember the famous statement of Laplace, "An intelligence which knew at a given instant all of the forces by which nature is animated and the relative position of all the objects, if it were in addition sufficiently powerful to analyze all of this information, would include in one formula the movements of the most massive objects in the universe and those of the lightest atom; nothing would be uncertain to it; and the future as the past, would be present to its eyes." The reader of 1814 was right if from the words of Laplace he anticipated that progress would be made in learning the laws of motion. But he was wrong if he thought one would uncover the rationale of the initial conditions. No more today than then does one know the how and the why of the positions and the velocities with which components of a dynamical system are first set into motion. We can imagine that space, executing its dynamics in one region of superspace, gives a universe with one number of particles and one set of particle masses; and space executing its dynamics in another region of superspace gives a universe with another number of particles and with another set of particle masses. But why then do we happen to be living in the part of superspace where we find ourselves?

No one who reflects on these transcendental issues can fail to find thought-provoking a suggestion made by Dicke, half jokingly, half seriously. What sense does it have, he asks, to speak about a universe unless that universe contains intelligent beings? But intelligence implies a brain. And a brain cannot come into being without life. As the foundation for life no biochemist sees any alternative but DNA. But DNA demands carbon for its construction. Carbon in turn comes into being by thermonuclear combustion in the stars. Thermonuclear combustion demands billions of years of time. But according to general relativity a universe cannot provide billions of years of time unless it also has billions of light years of extent. On this view it is not the universe that has dominion over man, but man who governs the size of the universe!

We are in no position to assess Dicke's suggestion today. However, one commentary will occur to everyone. If the necessity for the existence of mind governs the scale of the cycle of the universe, and if in turn the scale of the universe governs the number and sizes of the particles, then it is fruitless to think of a simple magic formula that would give once and for all the mass of the proton and the mass of the electron!

One takes up such suggestions and allows himself such commentaries not in any hope that they will provide answers, but only with the thought that they will suggest to us how deep are the questions that confront us —and how we may perhaps go about formulating the issues. Deep though they are, and almost theological in character though they seem, they are still questions which we could not and would not pose as we do if the concept of superspace were not at hand as framework for the discussion.

Superspace, the arena in which space lives out its dynamics: no consequence of the union of the quantum principle with Einstein's geometrodynamics is more revolutionary, and none seems more likely to have consequences for all of physics, from elementary particle physics to the dynamics of the universe. The "wave equation" that Schroedinger gave the world in 1925 was simple and definite, and out of it he quickly found the energy levels of the hydrogen atom. Little did he—or anyone—at first realize that his equation was a time bomb in the heart of physics. The explosion it produced gave us such revolutionary concepts as "probability amplitude," "probability current," the "uncertainty principle," and "complementarity." Schroedinger himself once said that if he had known what it was all going to lead to he would have had nothing to do with it, only to be told by Bohr, "All of us, however, are grateful to you!" How much of present-day chemistry, metallurgy, nuclear physics, and communications science would be beyond our grasp without Schroedinger's equation!

A Time Bomb with Revolutionary Consequences

If the Schroedinger equation was a time bomb, is quantum geometrodynamics a super-time bomb? Already one can see revolutionary consequences: superspace; the failure of the idea of time at small distances; quantum fluctuations in the geometry of space; "coupling between alternative histories of the universe" in the final stages of gravitational collapse. But the questions we have been led to ask about initial conditions seem destined to force us into still more revolutionary concepts. At the heart of quantum geometrodynamics lies a dynamic equation, what one might perhaps call the "Einstein-Schroedinger" equation, when remaining uncertainties about the exact details of its form are cleared up. This equation, like every equation, admits of initial conditions. Proper specifications of the initial conditions, however, are out of the question for anyone who limits his attention to one dynamical history of the universe. By necessity, he has to give probability amplitudes for a wider variety of possible alternative configurations for space before he can predict with the help of the wave equation the evolution of the dynamics throughout the rest of superspace. What possible sense does it make to specify initial conditions in this way? One cannot ask questions such as these without recognizing that the problem of initial conditions, new form though it has in quantum geometrodynamics, poses issues which are as far beyond our reach today as they were at the time of Laplace.

If these issues about initial conditions are "theological" in character then also one cannot escape the fact that theological considerations have their influence on human actions. In 1952 an acquaintance, traveling through one of the greatest of the nations of South Asia, noting how many children were dying whose lives might have been saved by smallpox innoculations, could not forbear to express his dismay to the Minister of

Education. That official could not have been less concerned. "After all, what difference does it make; they will be reincarnated anyway." My colleague, Frederick Mote, a distinguished student of Chinese history and philosophy, in a recent address attributed the difference between Chinese outlooks and sense of values and those of the West to nothing more central than their different view of cosmology. That cosmology, he noted, has in it no creation and no creator; what goes on is "a process in which all stages are simultaneously present"; what governs it is "a set of logical, not of chronological relationships." If we want to see how, also in the West, considerations beyond physics color outlooks, we have only to turn to the words of William James: "Actualities seem to float in a wider sea of possibilities from out of which they were chosen; and *somewhere*, indeterminism says, such possibilities exist, and form part of the truth."

One cannot touch thus peripherally on "theology" without recalling the great debates of long ago. One cannot forget that they eventually opened the door to modern science, which demands that we communicate with one another in understandable words, free of all mysticism. When the Bishop of Paris ruled in 1227 that it is wrong to deny God's power to create as many worlds as He pleases, he did not stop controversy; he augmented it. A hundred years later "one of the most devastatingly critical thinkers of all ages," William of Ockham, stressed that "God's will remained the final arbiter; but just because it could not be circumscribed or defined it was necessary to look to what could be known . . . by measurement and observation . . . as the foundation of practical knowledge." Gordon Leff goes on to remind us that, "As a result, physics, mechanics, mathematical calculations and geometry all reached a new flowering during the 14th and 15th centuries."

We have looked at the billiard balls batting about the billiard table. We have found ourself asking new questions about the beginning and the end. Thanks to the labors of many workers in the days since Einstein's death, we have in our hands in quantum geometrodynamics a new conceptual framework of unprecedented scope to deal with these questions, a structure built out of the two over-arching principles of twentieth-century physics. As we explore the new and revolutionary content of this conceptual framework, we do so resolved to hold fast at all costs to the centuries-old scientific tradition of the West.

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