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THE LESSON OF THE BLACK HOLE*

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(Read April 20, 1979 in the Albert Einstein Centenary Symposium)

BLACK HOLE AS "GATE OF TIME"

Time ends. That is the lesson of the "big bang." It is also the lesson of the black hole, closer at hand and more immediate object of study.

The black hole is a completely collapsed object. It is mass without matter.

The Cheshire cat in *Alice in Wonderland* faded away leaving behind only its grin. A star that falls into an already existing black hole, or that collapses to make a new black hole, fades away. Of the star, of its matter and of its sunspots and solar prominences, all trace disappears. There remains behind only gravitational attraction, the attraction of disembodied mass. This gravitational attraction continues to hold in circumferential orbit any planet that was already in orbit around the star while it still lived.

Besides its continuing gravitational attraction, the two principal features of the black hole are the point of crunch or "singularity" at its center and—further out, at the so-called "Schwarzchild radius"—the perimeter of no return for someone or something approaching from outside. This perimeter is commonly referred to as the "horizon" of the black hole. A traveler approaching in a spaceship feels no bump or jar as he crosses this unmarked boundary. But once inside it he cannot escape, no matter how powerful his rocket engine. Neither can any light signal or radio message. They, like him and his ship, contribute nothing but blackness to a faraway observer. Within a short and firmly fixed time the signals and the travelers are obliterated at the central singularity, the point of crunch.

In no easy way can one get a more vivid impression of the distinction between the horizon and the crushing point than to fall head first over a cliff onto the rocks below. As one's head recovers in the hospital afterwards one remembers first the final crunch and only later the wet grass growing at the top. On first approach it had sloped down safely, inviting the explorer to come closer. Unperceived in one's eagerness to peer over the edge, the slope of the slippery grass increased. Then the shoes began to slide forward. Suddenly it became clear that disaster was inescapable, though it had not yet struck. That treacherous and unmarked point of no return symbolizes the equally treacherous and equally unmarked horizon of the black hole—as the rocks at the bottom symbolize the point of obliteration, not only of matter but of the very spacetime that immediately envelops that matter.

Several books and hundreds of research papers have been written about the physics of black holes.[1] A bibliography of the subject makes all by itself a substantial book. Almost all of this work deals with conditions outside the horizon, conditions different in degree but similar in kind to what one finds outside such compact astronomical objects as white dwarf stars and neutron stars. However, the really new physics lies inside the horizon, at the point of crunch.

At the central singularity time comes to an end.

What happens at this ending of time? What kind of "process" is it that obliterates, not only the signals and the traveler and his spaceship, but even the astronomical Niagara Falls of star matter itself, roaring inward to its death?

In the gravitational collapse, not only of matter, but of the spacetime geometry enveloping that matter surely something new and strange is going on, something of deep import to our understanding of the nature of this world.[2]

A motion picture of the gravitational collapse at the

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* Paper given at the April, 1979, meeting of the American Philosophical Society, as revised for publication. Preparation for publication assisted by the University of Texas Center for Theoretical Physics and by National Science Foundation Grant PHY78-26592.

[1] Among introductory articles are R. Ruffini and J. A. Wheeler, "Introducing the black hole," *Physics Today* **24** (1971): pp. 30–36; R. Penrose, "Black holes," *Scientific American* **226** (May 1972): pp. 38–46 and K. S. Thorne, "The search for black holes," *Scientific American* **231** (December 1974): pp. 32–43. Two elementary books are H. L. Shipman, *Black Holes, Quasars and the Universe* (Houghton Mifflin, Boston, 1976) and W. Sullivan, *Black Holes, the Edge of Space, the End of Time* (Anchor Press, Doubleday, Garden City, N.Y., 1979). More advanced texts include C. DeWitt and B. DeWitt, eds., *Black Holes,* Les Houches 1972, Lectures delivered at the Summer School of Theoretical Physics of the University of Grenoble (Gordon and Breach, New York, 1973); M. Rees, R. Ruffini, and J. A. Wheeler, *Black Holes, Gravitational Waves and Cosmology: An Introduction to Current Research* (Gordon and Breach, New York, 1974); H. Gursky and R. Ruffini, *Neutron Stars, Black Holes and Binary X-ray Sources* (D. Reidel, Dordrecht, Holland, 1975); R. Giacconi and R. Ruffini, *Physics and Astrophysics of Neutron Stars and Black Holes* (North-Holland, Amsterdam, 1978).

[2] For more on the nature of the issue see J. A. Wheeler, "Frontiers of Time," in N. Toraldo di Francia and Bas van Frassen, eds., *Problems in the Foundations of Physics*, Rendiconti della Scuola Internazionale di Fisica 'Enrico Fermi', LXXII Corso (North-Holland, Amsterdam, 1979) and J. A. Wheeler, "Beyond the Black Hole," in H. Woolf, ed., *Some Strangeness in the Proportion: A Centennial Symposium to Celebrate the Achievements of Albert Einstein* (Addison-Wesley, Reading, Mass., 1980).

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singular center of a black hole, run backwards, differs in no known way from a motion picture of the big bang. The mystery of how matter—and spacetime itself—can fade out of existence is part and parcel of the mystery of how the world came into being.

Matter thus has a beginning and an end. So does spacetime. Time itself has a beginning and an end. Einstein's theory of gravitation provides no place whatsoever for a "before" before the big bang, no place for an "after" after gravitational collapse.

There are many ways to put the lesson of the black hole; but it is difficult to find one better suited to lead to new insights than this: time cannot be an ultimate category in the description of nature. Time is not a primordial and precise concept; it must be secondary, derivative, and approximate.

Time and spacetime we generally picture as ideal mathematical continua. A transparent sheet of quartz also looks like an ideal mathematical continuum, and so does a piece of cloth. Nowhere more clearly than at a crack does a crystal show that it cannot be a continuum. Nowhere more clearly than at its selvages, where the threads turn under (fig. 1), does a piece of cloth show that it cannot be a continuum. Nowhere more clearly than at the "gates of time"—big bang and collapse—does spacetime show that it cannot be an ideal continuum. The crystal is made of molecules; the cloth is woven from thread. Spacetime geometry, we have to believe, is likewise built of some substrate, call it "pregeometry" or call it what we will.

Motive for unraveling pregeometry in the coming decades we have in plenty from reflecting on the gates of time; and motive to reflect on the gates of time we have in plenty from the black hole.

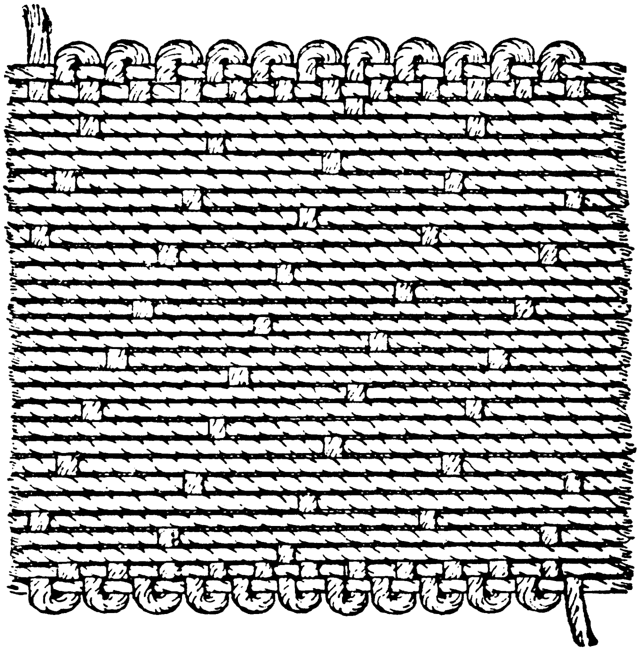

FIG. 1. Nowhere more clearly than at its selvages does cloth disclose that what looks like a continuum is constructed out of a special building material, thread.

MICHELL, LAPLACE AND 18TH CENTURY FORESHADOWINGS OF THE BLACK HOLE

The concept of black hole is old, although the term itself was coined only in 1967. As early as 1783 John Michell argued (fig. 2) that light must "be attracted in the same manner as all other bodies" and therefore, if the attracting center is sufficiently massive and sufficiently compact "all light emitted from such a body would be made to return towards it."[3] Pierre-Simon Laplace, apparently independently, came to the same conclusion in 1795 and went on to reason that "it is therefore possible that the greatest luminous bodies in the universe are on this very account invisible."[4]

In these days of space voyages the basic idea appears simple enough. A speed of 2.4 km/second is required to launch a rocket from the Moon; 11 km/s, from the Earth; 618 km/s, from the Sun; and of the order of 30,000 km/s from a typical "pulsar" or "neutron star," the most compact object we know short of a black hole. When a body of five solar masses collapses to a configuration so compact that the calculated launch velocity exceeds the speed of light, 300,000 km/s, escape is impossible.

Michell and Laplace used Isaac Newton's "action at a distance" theory of gravitation in analyzing escape of light from, or its capture by, an already existing compact object, considered to be static. But is any such static object possible? And if not, then what? Gravitational collapse?

GRAVITATIONAL COLLAPSE AND EINSTEIN'S THEORY OF GRAVITATION

A proper treatment of these issues demands a proper theory. This Einstein gave us in his 1915 and still standard geometric theory of gravitation.[5] The central idea of this theory lends itself to statement in a single

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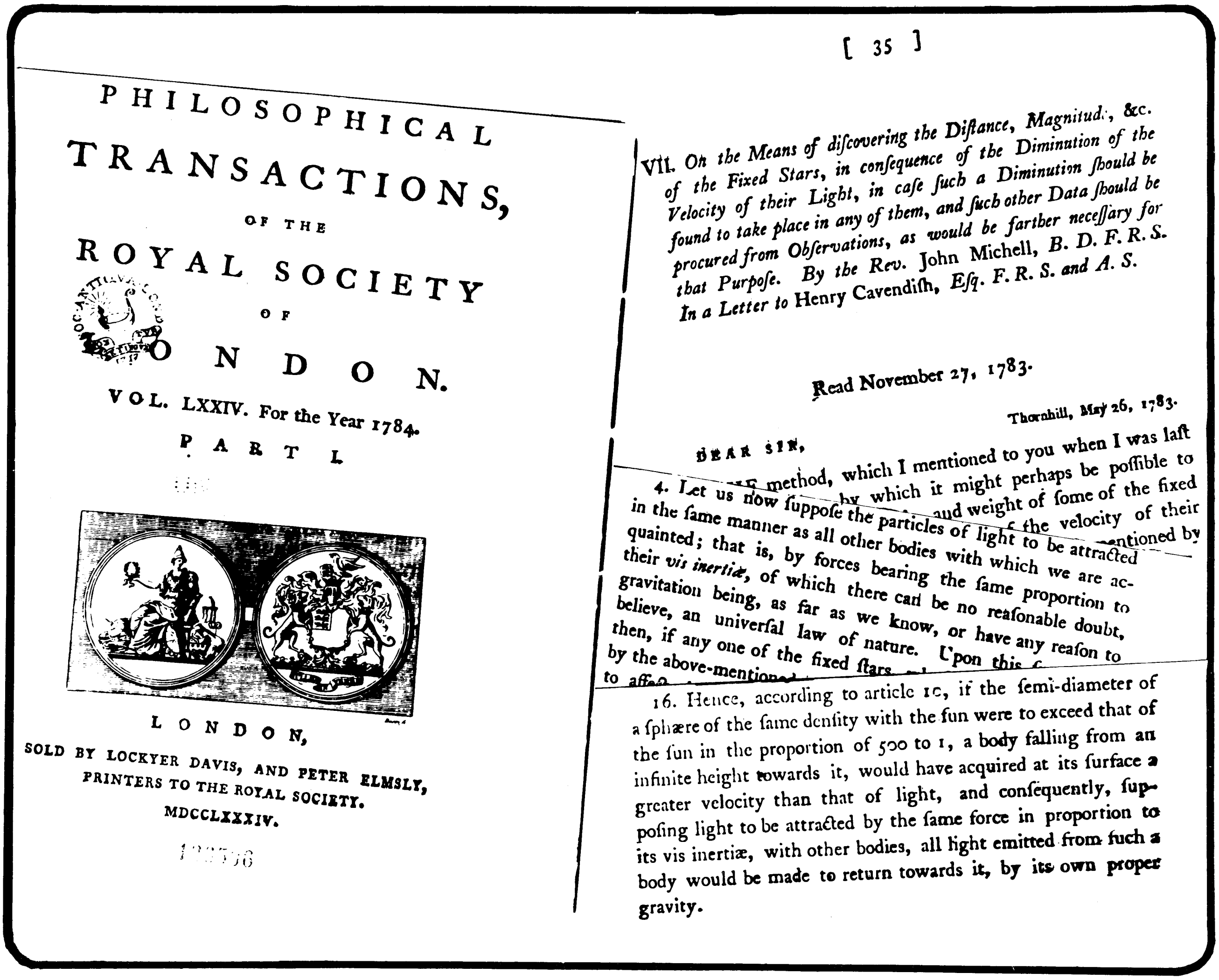
[3] J. Michell, "On the means of discovering the distance, magnitude, &c. of the fixed stars, in consequence of the diminution in the velocity of their light, in case such a diminution should be found in any of them, and such data should be procured from observations, as would be further necessary for that purpose," *Philosophical Transactions* [*of the Royal Society, London*] **74:** pp. 35–57 (1784) (read November 27, 1783); cited and discussed in S. Schaffer, "John Michell and black holes," *Journal for the History of Astronomy* **10:** pp. 42–43 (1979).

[4] P.-S. Laplace, *Exposition du système du monde* (Cercle-Social, Paris, **2**, 1795), p. 305; mathematical calculations underlying this conclusion given in an essay of Laplace which in modern English translation [in S. W. Hawking and G. F. R. Ellis, *The Large Scale Structure of Space-Time* (Cambridge University Press, Cambridge, U.K., 1973), pp. 365–368] is titled "Proof of the theorem, that the attractive force of a heavenly body could be so large, that light could not flow out of it," in *Allgemeine geographische Ephemeriden herausgegeben von F. von Zach*, IV Bd., I st., I Abhandl. (Weimar, 1799).

[5] A. Einstein, "Die Feldgleichungen der Gravitation," *Preuss. Akad. Wiss. Berlin, Sitzber.*, pp. 844–847 (1915).



PHILOSOPHICAL
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PART I.

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[35]

VII. *On the Means of diſcovering the Diſtance, Magnitude, &c. of the Fixed Stars, in conſequence of the Diminution of the Velocity of their Light, in caſe ſuch a Diminution ſhould be found to take place in any of them, and ſuch other Data ſhould be procured from Obſervations, as would be farther neceſſary for that Purpoſe. By the Rev.* John Michell, *B. D. F. R. S. In a Letter to* Henry Cavendiſh, *Eſq. F. R. S. and A. S.*

Read November 27, 1783.

Thornhill, May 26, 1783.

DEAR SIR,

method, which I mentioned to you when I was laſt
by which it might perhaps be poſſible to
and weight of ſome of the fixed
the velocity of their
mentioned by

4. Let us now ſuppoſe the particles of light to be attracted in the ſame manner as all other bodies with which we are acquainted; that is, by forces bearing the ſame proportion to their *vis inertiæ*, of which there can be no reaſonable doubt, gravitation being, as far as we know, or have any reaſon to believe, an univerſal law of nature. Upon this
then, if any one of the fixed ſtars
by the above-mention
to affe

16. Hence, according to article 10, if the ſemi-diameter of a ſphære of the ſame denſity with the ſun were to exceed that of the ſun in the proportion of 500 to 1, a body falling from an infinite height towards it, would have acquired at its ſurface a greater velocity than that of light, and conſequently, ſuppoſing light to be attracted by the ſame force in proportion to its vis inertiæ, with other bodies, all light emitted from ſuch a body would be made to return towards it, by its own proper gravity.

FIG. 2. The words of John Michell, first to foreshadow the black hole. Reproduced from the copy of the *Philosophical Transactions* in the Library of the University of Texas with the permission of the Royal Society (Montage was made by Adrienne Harding).

sentence: Space tells matter how to move, and matter tells space how to curve.[6]

One whose house was finished on time, so that his family could move in as scheduled, will be forgiven for remembering that September 1, 1939, was a Friday. The newspaper appeared that day ablaze with headlines. They announced the joint German-Soviet invasion of Poland, marking the start of World War II.

The *Physical Review* came out the same day in its usual green cover. In it one paper analyzed the mechanism of nuclear fission, explained why the rare isotope of uranium, 235, has to be regarded as highly fissile, and provided the basis to see that plutonium 239, which does not even exist in nature, must also be highly fissile.[7] These two substances were to end World War II.

In the same issue of the *Physical Review*, five pages later, appeared a paper by Robert Oppenheimer and Hartland Snyder (fig. 3), the first detailed treatment of gravitational collapse within the framework of Einstein's theory of gravitation.[8] For simplicity they treated the collapsing system as a collection of dust particles so well separated one from another that all problems of pressure and temperature can be overlooked. Each particle moves freely under the gravitational attraction of all the others.

Oppenheimer and Snyder showed that the collapse will have quite a different appearance according as it is studied by a faraway observer or a traveler falling

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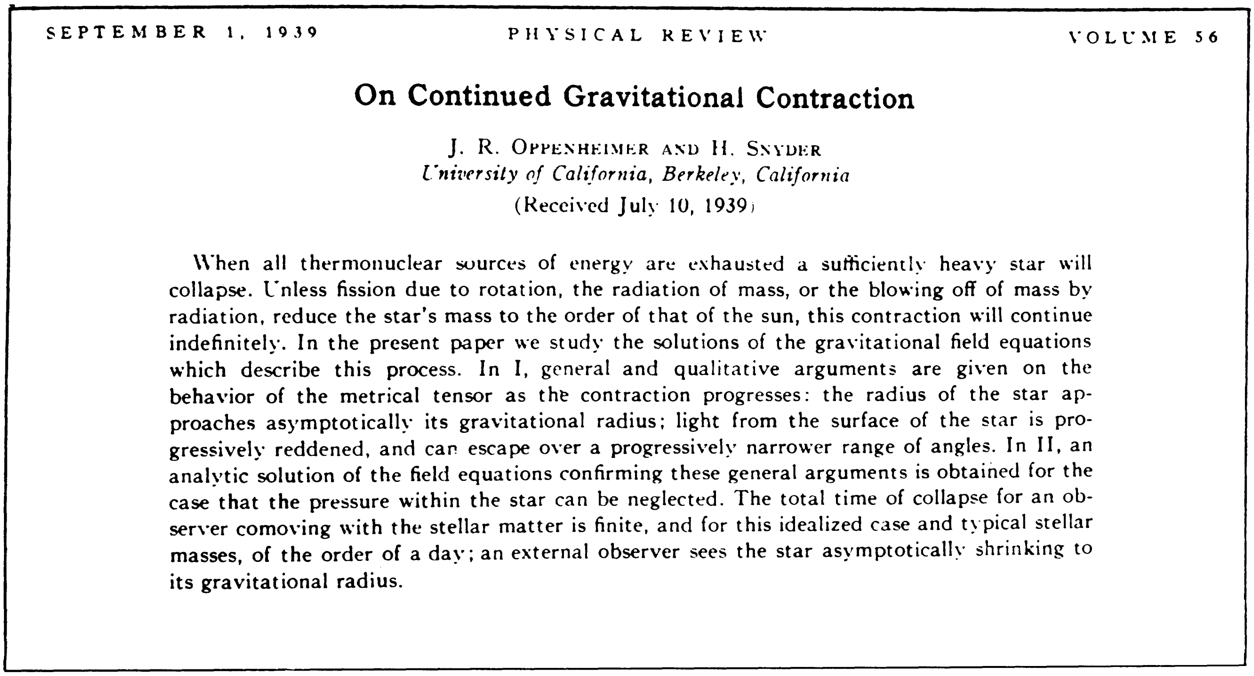
[6] Wording adapted from C. W. Misner, K. S. Thorne, and J. A. Wheeler, *Gravitation* (W. H. Freeman and Company, San Francisco, 1973), p. 5.

[7] N. Bohr and J. A. Wheeler, "The mechanism of nuclear fission," *Physical Review* **56:** pp. 426–450 (1939).

[8] J. R. Oppenheimer and H. Snyder "On continued gravitational collapse," *Physical Review* **56:** pp. 455–459 (1939).



SEPTEMBER 1, 1939 PHYSICAL REVIEW VOLUME 56

On Continued Gravitational Contraction

J. R. OPPENHEIMER AND H. SNYDER
University of California, Berkeley, California
(Received July 10, 1939)

When all thermonuclear sources of energy are exhausted a sufficiently heavy star will collapse. Unless fission due to rotation, the radiation of mass, or the blowing off of mass by radiation, reduce the star's mass to the order of that of the sun, this contraction will continue indefinitely. In the present paper we study the solutions of the gravitational field equations which describe this process. In I, general and qualitative arguments are given on the behavior of the metrical tensor as the contraction progresses: the radius of the star approaches asymptotically its gravitational radius; light from the surface of the star is progressively reddened, and can escape over a progressively narrower range of angles. In II, an analytic solution of the field equations confirming these general arguments is obtained for the case that the pressure within the star can be neglected. The total time of collapse for an observer comoving with the stellar matter is finite, and for this idealized case and typical stellar masses, of the order of a day; an external observer sees the star asymptotically shrinking to its gravitational radius.

FIG. 3. The first detailed analysis of collapse within the framework of Einstein's geometrical theory of gravitation.

in with, and at the outskirts of, the cloud of dust. The voyager will arrive in a very short time at a condition of infinite gravitational stress. If he sends out a radio "beep" every second of his existence, he will get off only a limited number of messages before the collapse terminates and his existence ends. In contrast, the faraway observer will receive these beeps at greater and greater time intervals; and, wait as long as he will, he will never receive any of the signals given out by the traveler between his crossing of the intangible horizon and his arrival at the central singularity. Moreover, the cloud of dust will appear to the faraway observer, not to be falling ever faster, but to slow up and approach asymptotically a limiting sphere with the dimensions of the horizon. As it freezes down to this standard size it grows redder and fainter by the instant, and quickly becomes invisible.

GRAVITATIONAL COLLAPSE: NEVER-NEVER LAND OR LIVE PHYSICS?

Why did this important paper not initiate black hole physics? First World War II drew attention to more immediate issues. Second, after World War II other fields of physics claimed the attention of the physics community—and of Oppenheimer himself. Third, it was difficult for many to accept the idea that gravitational collapse was anything more than a hypothetical pencil and paper process, that it had anything to do with real astrophysics.[9] Fourth, it was repugnant to believe that matter could be infinitely compacted in a finite time. Why accept a difficulty from which physics could see no way out?

Exactly this greatest difficulty of the subject, however, proved its greatest attraction for someone finding himself in the academic year 1952–1953 giving for the first time a graduate course on general relativity. That course provided a marvelous opportunity to review with a bright and eager group of student colleague-collaborators the meaning and applications of Einstein's theory of gravitation and also the issues it poses. Of them all, none stood out as more clearly deserving of attention than gravitational collapse; and in collapse no greater mystery than what happens in the final crunch.

IS THERE ANY WAY TO ESCAPE COLLAPSE?

Do we know enough about matter to be sure that it cannot successfully oppose collapse? We understand electromagnetic radiation better than we understand the behavior of matter at high density. Then why not consider a star containing no matter at all, an object built exclusively out of light, a "gravitational electro-

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[9] See for example the remarks of J. R. Oppenheimer at the end of the discussion of gravitational collapse at the 11th Solvay Congress, in Institut international de physique Solvay, *La structure et l'évolution de l'univers* (Stoops, Brussels, 1958) following p. 148. Oppenheimer withdrew to a bench in the corridor when gravitational collapse was being discussed at the December, 1963, Dallas International Symposium on Gravitational Collapse and Relativistic Astrophysics, the proceedings of which were subsequently published by the University of Chicago Press under the editorship of E. Schücking.

magnetic entity" or "geon," deriving its mass solely from photons, and these photons held in orbit solely by the gravitational attraction of that very mass?[10] It turned out that a geon has the stability—and the instability—of a pencil standing on its tip.[11] The geon does not let its individual photons escape any more than the pencil lets its individual atoms escape. But that swarm of photons, collectively, like the assembly of atoms that make up the pencil, collectively, can fall one way or the other. Starting at first slowly it can expand outward more and more rapidly and explode into its individual photons. Equally easily, it can fall the other way at first slowly, then more and more rapidly to complete gravitational collapse. Thus it did not save one from having to worry about gravitational collapse to turn from matter to "pure" radiation.

Then a closer look at matter itself showed that "the harder it resists, the harder it falls": pressure itself has weight, and that weight creates more pressure, a "regenerative cycle" out of which again the only escape is collapse.[12]

COLLAPSED OBJECTS AS REAL OBJECTS

More and more insistently at this point an issue clamored for attention: collapse to *what*? This was and remains the great problem of a great subject, and one to which we must return at the end for a final assessment. To one wrestling with it, not merely day after day, but year after year, the question of the outcome became all absorbing and took on a life of its own. This issue of gravitational collapse cannot be a mere pencil and paper question, one found oneself reflecting and saying; these completely collapsed objects cannot be purely imaginary; somewhere they must exist and form a part of reality. Normal stars exist, some millions of kilometers across. White dwarfs exist, a few thousand kilometers across. Neutron stars had been calculated to exist, from a few kilometers to a few tens of kilometers across. One had enough faith in neutron stars[13] to encourage and applaud every effort[14] to find one. Surely one was right in stressing equally that a completely collapsed object must also exist and must also be searched for. Then, in 1967, came the discovery of pulsars,[15] astronomical objects sending out radio signals each with its own characteristic timing, maintained day after day with fantastic fidelity. What were they? An intense discussion on the issue took place at the NASA Institute for Space Studies in New York, late the same year. Candidates were put forward of the greatest variety, from planetary objects in orbit to completely collapsed objects in orbit and from vibrating white dwarfs to rotating neutron stars—what we know today to be responsible. The psychological barrier against even talking of entities as hypothetical as "completely collapsed objects" was dissolved away in the course of the meeting when the term "black holes" was introduced to describe them[16]—and black holes they have remained ever since. Physicists like patients only really believe they know what their trouble is when a physician has given it a name.

Nothing did more to establish that the pulsars are neutron stars, rotating on their axes, than the constancy with which they flash, better timekeepers than the normal watch; and nothing did more than the discovery of these compact objects, 10 to 100 km across, to encourage the search for a still more compact object, a completely collapsed star, a black hole.

It is one thing to want to find a black hole and quite another to propose a means to find one. How can one think of seeing a black object less than 10 km across lost in the depths of space when it was a great feat even to see for the first time on December 4, 1639, Venus, 12,000 km in diameter, swimming across the brightly illuminated disc of the Sun?[17]

THREE MEANS OF OBSERVATION

Three means offer themselves to detect a black hole: (1) a pulse of gravitational radiation given out at the time of formation, (2) the gravitational pull of the black hole on a companion star, and (3) the luminosity of the matter streaming into the black hole.

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[10] J. A. Wheeler, "Kugelblitz," abstract of paper, American Physical Society, early 1950's; J. A. Wheeler, "Geons," *Physical Review* **97** (1955): pp. 511–536.

[11] Geon as unstable with respect to collective gravitational collapse: J. A. Wheeler, "Geometrodynamics and the issue of the final state," pp. 315–520 in C. DeWitt and B. DeWitt, eds., *Relativity, Groups and Topology* (Gordon and Breach, New York, 1964), see especially pp. 500–501.

[12] Chapter 4, "Central density and the regeneration of pressure," B. K. Harrison, K. S. Thorne, M. Wakano, and J. A. Wheeler, *Gravitation Theory and Gravitational Collapse* (University of Chicago Press, Chicago, 1965); detailed analysis of models of pressure regeneration in J. A. Wheeler, "The degenerate star: a relativistic catastrophe," a chapter in H.-Y. Chiu and W. F. Hoffman, eds., *Gravitation and Relativity* (W. A. Benjamin, New York, 1963).

[13] Rotation of a neutron star as a storehouse of energy to power the Crab Nebula: J. A. Wheeler, "Superdense stars," *Annual Reviews of Astronomy and Astrophysics* **4** (1966): pp. 393–432.

[14] H. Friedman, "X-ray astronomy," *New Scientist* **28** (1965): pp. 904–906; H. Friedman, "Rocket astronomy," *Annals of the New York Academy of Sciences* **198** (1972): pp. 267–273.

[15] A. Hewish, S. J. Bell, J. D. H. Pilkington, P. F. Scott, and R. A. Collins, "Observation of a rapidly pulsating radio source," *Nature* **217** (1968): pp. 709–713.

[16] J. A. Wheeler, name "black hole" in "Our universe: the known and the unknown," address before the American Association for the Advancement of Science, New York, December 29, 1967, in *American Scholar* **37:** pp. 248–274 (1968) and *American Scientist* **56:** pp. 1–20 (Spring 1968), and in R. Ruffini and J. A. Wheeler, "Introducing the black hole," *Physics Today* **24:** pp. 30–36 (1971) and in "The black hole," pp. 279–316 in *Astrophysics and Gravitation: Proceedings of the Sixteenth Conference on Physics at the University of Brussels, September 1973* (Editions de l'Université de Bruxelles, 1040 Bruxelles, Belgium, 1974).

[17] Transit calculated by Jeremiah Horrox, young curate of Hoole near Preston in Lancashire, England; almost missed because he conscientiously conducted his scheduled church service that Sunday afternoon; but to his joy seen just afterwards, with the black disc of the planet moving across the hundred times larger Sun.

Gravitational waves have never yet been detected directly. There is indirect evidence for the loss of energy in the form of gravitational waves in one double star system.[18] It, however, has nothing directly to do with any black hole. There is intense effort underway to develop a detector of gravitational radiation.[19] So far, however, detection of the formation of a black hole by a pulse of gravitational radiation is a hope of the future.

The best available source of evidence for a black hole comes from the combination of methods (2) and (3), evidence for gravitational pull plus luminosity of accreting matter.

The domed-over stadium gives no evidence to the traveler flying overhead of the crowd within. However, he sees the lines of traffic converging on it from all directions, becoming more and more tightly packed in traffic jams as they approach the center of attraction. A black hole whirling in orbit about, and being whirled in orbit by, a normal star will also be the recipient of clouds of gas from this companion, with all the puffs and swirls that one can imagine from watching a factory chimney belch its clouds of smoke. This gas will not fall straight in. It will orbit the black hole in ever tighter spirals as it works its way inward, making "weather" on the way. It, like the traffic approaching the stadium, will be squeezed more and more. Through this compression it will be driven up to higher and higher temperatures, temperatures estimated to be of the order of tens of millions of degrees. Gas so highly heated will emit electromagnetic radiation copiously and—if the black hole is of normal stellar mass—primarily in the x-ray region of the spectrum. This x-ray emission will not be steady. It will fluctuate. This combination of fluctuating x-ray emission and gravitational pull on a companion is the best authenticating "signature" that one presently knows for a black hole.

CYGNUS X-1 AND OTHER BLACK HOLES

Bruno Rossi, Herbert Gursky, Ricardo Giacconi and their colleagues at the Massachusetts Institute of Technology and at Harvard University pioneered a series of ever more powerful x-ray telescopes in orbit above the Earth.[20] Without that achievement there would have been no hope of detecting any x-rays at all from space because this radiation is strongly absorbed in the Earth's atmosphere. With the help of this telescope they found dozens of localized x-ray sources and among them one in the constellation Cygnus.[21] The location as best it could be pinned down at the time of discovery is framed with white lines in figure 4. An optical telescope directed at that region of the sky found there a star, "HDE 226868," clearly a member of a double star system because it moves back and forth a distance of 5.2×10^6 km in the line of sight with a 5.6-day period. Its mass, from two lines of evidence (spectral character and absolute luminosity) is concluded to be of the order of twenty-five solar masses. The invisible component, in order to swing by its gravitational pull so big a visible mass back and forth so great a distance in so short a time, has to be of the order of ten solar masses, and certainly greater than five solar masses, one reasons. An ordinary star of this mass would be quite visible in the optical, quite invisible in the x-ray spectrum. This, therefore, is not an ordinary star. Moreover, it is too heavy to be a white dwarf or a neutron star. It gives off x-rays—flickering x-rays. No one sees any natural and reasonable interpretation for it except as a black hole. That is not the only observational evidence for a black hole.

Bursts of x-rays suggest a black hole of a hundred to a thousand solar masses at the center of each of five clusters of stars in our own galaxy.[22] Charles Townes and his colleagues,[23] Jan Oort,[24] and others[25] give considerations arguing for a black hole of about 4×10^6 solar masses at the center of the Milky Way.

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[18] J. H. Taylor, L. A. Fowler and P. M. McCulloch, "Measurement of general relativity effects in the binary pulsar PSR1913+16," *Nature* **277:** pp. 437–440 (February 8, 1979).

[19] See especially R. W. P. Drever, "Laser experiments on gravitational waves," *Proceedings of the Ninth International Conference on General Relativity and Gravitation,* Jena, July 14–18, 1980 (VEB Deutscher Verlag der Wissenschaften, Berlin, DDR, in publication).

[20] For an early summary see R. Giacconi, "Progress in x-ray astronomy," *Physics Today* **26:** no. 5 (1973): pp. 38–47.

[21] R. Giacconi, P. Gorenstein, H. Gursky, and J. R. Water, "An x-ray survey of the Cygnus region," *Astrophysical Journal Letters* **148:** pp. L119–L127 (June 1967); this and subsequent literature will be found in H. Gursky and R. Ruffini, *Neutron Stars, Black Holes and Binary X-ray Sources* (D. Reidel, Dordrecht, Holland, 1975); and R. Giacconi and R. Ruffini, *Physics and Astrophysics of Neutron Stars and Black Holes* (North-Holland, Amsterdam, 1978).

[22] J. E. Grindlay, "Two more globular-cluster x-ray sources?" *Astrophysical Journal Letters* **224:** pp. L107–L111 (1977).

[23] E. R. Wollman, "Ne II 12.8 μ emission from the galactic center and compact H II regions" (doctoral thesis, University of California, Berkeley, 1976; available from University Microfilms, Ann Arbor, Michigan 48106); E. R. Wollman, T. R. Geballe, J. H. Lacy and C. H. Townes, "Spectral and spatial resolution of the 12.8 micron Ne II emission from the galactic center," *Astrophysical Journal Letters* **205:** pp. L5–L9 (1976); E. R. Wollman and C. H. Townes, "Ne II micron emission from the galactic center. II," *Astrophysical Journal* **218:** pp. L103–L107 (1977); J. H. Lacy, F. Baas, C. H. Townes, and T. R. Geballe, "Observations of the motion and distribution of the ionized gas in the central parsec of the galaxy," *Astrophysical Journal* **227:** pp. L17–L20 (1979).

[24] J. H. Oort, "The galactic center," *Astronomy and Astrophysics* **15:** pp. 295–362 (1977); see especially pp. 341, 343, 347, 349, 352; and on p. 353, "It is therefore possible that practically the whole of the $4–6 \times 10^6\ M_\odot$ deduced from the Ne II observations would be concentrated in the ultracompact radio source; it might be the mass of a black hole in the center."

[25] K. I. Kellermann, D. B. Shaffer, B. G. Clark, and B. J. Geldzahler, "The small radio source at the galactic center," *Astrophysical Journal* **214:** pp. L61–L62 (1977); L. F. Rodriguez and E. J. Chaisson, "The temperature and dynamics of the ionized gas in the nucleus of our galaxy," *Astrophysical Journal* **228:** pp. 734–739 (1979).

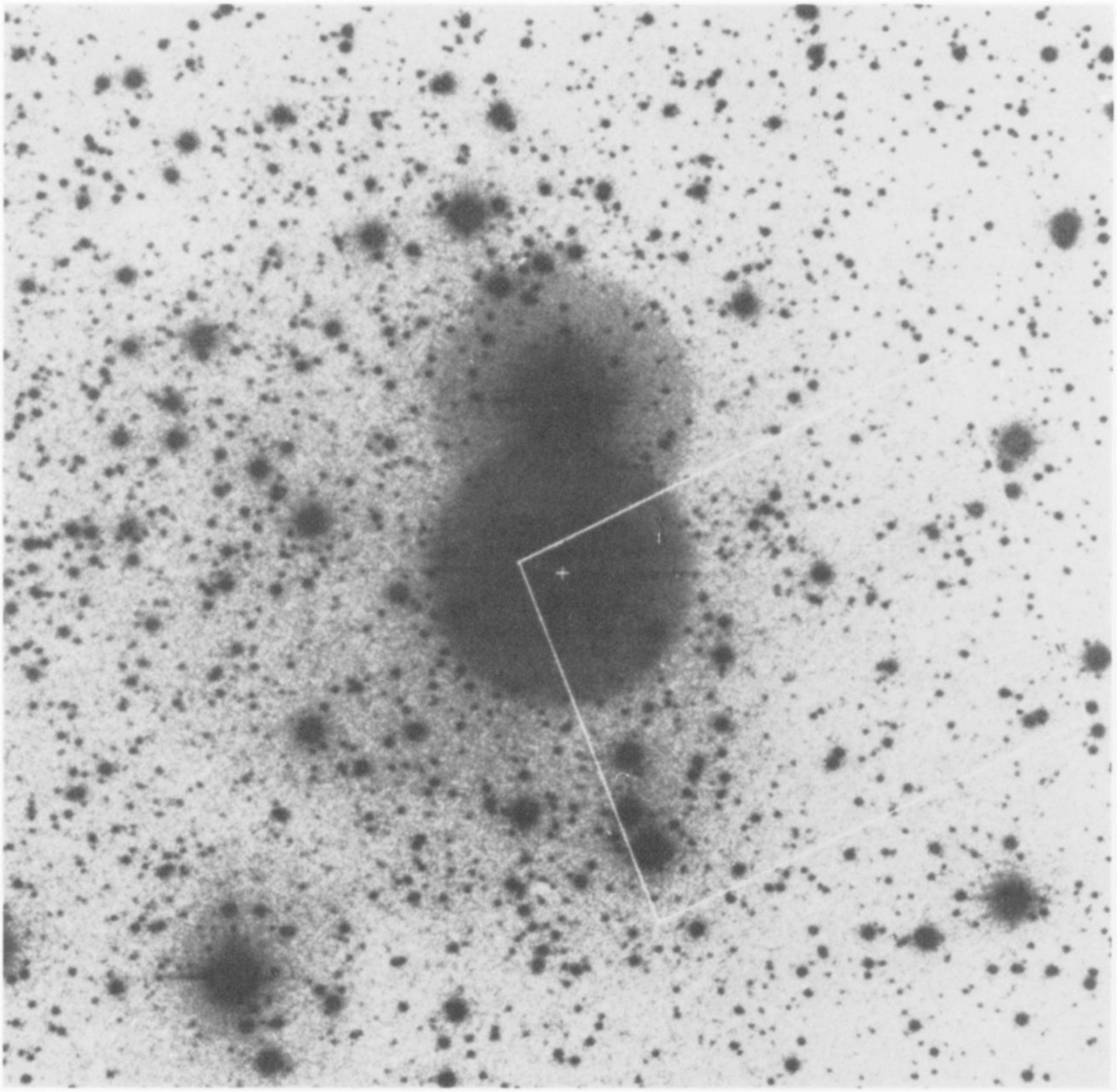

FIG. 4. An early step toward identifying the x-ray source Cygnus X1 as a black hole.

The Lick Observatory group and others find evidence[26] pointing to the possible existence of a black hole of about 5×10^9 solar masses at the center of the violently active galaxy M87.

How important are black holes? Are they rare? Or, are they more numerous than stars? Does their contribution to the mass content of the universe bulk larger than tangible matter? We don't know. Therefore it is not surprising that efforts yearly mount to determine an averaged-out figure for the effective content of mass-energy in the universe due to all sources together. This task is generally recognized to be one of the greatest of all challenges to the astrophysics of our time.[27]

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[26] P. J. Young, J. A. Westphal, J. Kristian, and C. P. Wilson, "Evidence for a supermassive object in the nucleus of the galaxy M87 from SIT and CCD area photometry," *Astrophysical Journal* **221:** pp. 721–730 (1978); W. L. W. Sargent and P. J. Young, "Dynamical evidence for a central mass concentration in the galaxy M87," *Astrophysical Journal* **221:** pp. 731–744 (1978); J. Stauffer and H. Spinrad, "Spectroscopic observations of the core of M87," *Astrophysical Journal Letters* **231:** pp. L51–L56 (1979).

[27] J. H. Oort, "Distribution of galaxies and the density of the universe," pp. 163–181 in Onzième Conseil de Physique Solvay: *La structure et l'évolution de l'univers* (Stoops, Brussels, 1958); J. R. Gott III, J. E. Gunn, D. N. Schramm, and B. M. Tinsley, "An unbound universe?" *Astrophysical Journal* **194:** pp. 543–553 (1974);

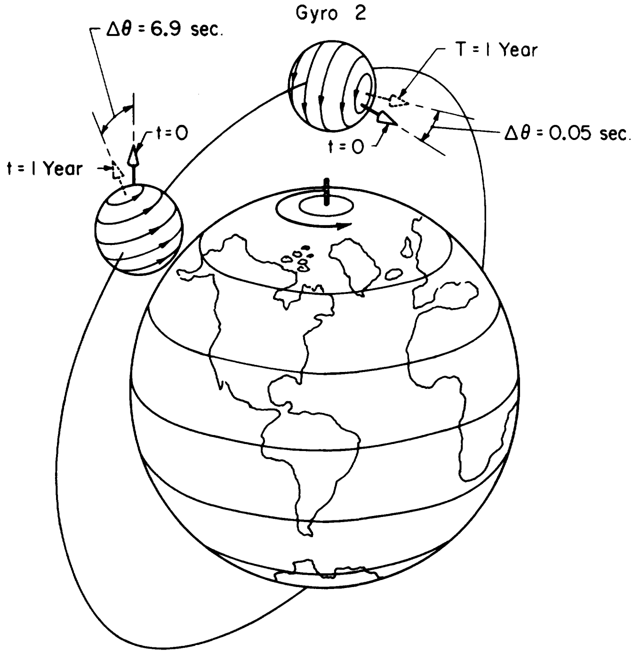

FIG. 5. Schematic representation of the proposed Stanford determination of the gyrogravitational effect produced by the spin of the Earth on its axis. In the course of one year, a gyro in a 500-mile-high polar orbit is predicted to turn in the direction of the Earth's rotation by one twentieth of a second of arc, the angle subtended by a dime at a distance of 70 km. The orbit would be the same, and the precession would be the same, if the Earth were collapsed to a black hole. The Schwarzschild radius of that black hole would be 0.88 cm.

FEATURES OF A BLACK HOLE

No one can speak about a black hole larger than the Sun without thinking of that German phrase for a glutton, *Nimmersatt*: the more it eats, the bigger it becomes; and the bigger it becomes, the more it eats. The black hole eats stars. No surprise, one could say; isn't that what gravitational attraction is all about? However, the Sun exerts gravitational attraction on the Earth, the Earth doesn't fall in, nor do any of the other planets. The reason is clear. They are going around with too much velocity, too much "angular momentum," to fall in. It takes time for a star circulating around a giant black hole to get rid of enough angular momentum to fall into the black hole. It nevertheless has some angular momentum when it makes the final plunge. As place to deliver up its angular momentum—and its mass—the ill-fated star has no alternative but the black hole itself. Therefore, the black hole usually contains angular momentum as well as mass.

The typical black hole is spinning. This is a very strange kind of spin. One cannot "touch one's finger to the flywheel" to find it. The flywheel, the black hole, is so immaterial, so purely geometrical, so untouchable, that no such direct evidence for its spin is available.

Evidence for the spin of the black hole is obtainable by indirect means. For this purpose it is enough to put a gyroscopic compass in polar orbit around the black hole. The gyroscopic compass, pointed originally at a distant star, will slowly sweep about the circuit of the heavens, in sympathy with the rotation of the black hole, but at a far slower rate. At work on the gyro, in addition to the normal direct pull of gravity, is a new feature of geometry predicted by Einstein's theory. This "gyrogravitational force" is as different from gravity as magnetism is different from electricity. An electric charge circling in orbit creates magnetism. A spinning mass creates gyrogravitation. We are far from being able today to observe the gyrogravitation of a spinning black hole. However an experiment is in active development by C. W. Francis Everitt and William M. Fairbank and their Stanford University colleagues to measure the gyrogravitational effect of the slow rotation of the Earth. For this purpose, they plan to put a gyroscope of unprecedented fidelity aboard a spacecraft into polar orbit around the Earth[28] (fig. 5).

What falls into a black hole thus carries in mass and angular momentum; and it can also carry in electric charge. These are the only attributes that a black hole conserves out of the matter that falls into it. All other particularities, all other details, all other physical properties of "matter" are extinguished (fig. 6). The resulting black hole, according to all available theoretical evidence, is completely characterized by its mass, its charge and its angular momentum, and by nothing more.

What does it mean to speak of the "size of a black hole"? No way of probing a black hole by any ordinary measuring device makes sense. A stick thrust toward it will be torn apart by gravitational pull. The lost end will be one more bit of matter to disappear from view, to be obliterated in the central crunch, and show up outside only as the gravitational attraction of immaterial mass. An immaterial mass has for its size an immaterial dimension that is the surface area of the horizon of the black hole, or its circumference, or still more conveniently, its circumference divided by 2π, the so-called "Schwarzschild radius" of the black hole.

The Schwarzschild radius is directly proportional to the mass: 3 km for a black hole of solar mass, 30 km for ten solar masses; 12 million km (17 × the ra-

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J. R. Gott III, J. E. Gunn, D. N. Schramm, and B. M. Tinsley, "Will the universe expand forever?" *Scientific American* **234**: pp. 62–79 (March 1976); M. Davis, E. J. Groth, and P. J. E. Peebles, "Study of galaxy correlations: evidence for the gravitational instability picture in a dense universe," *Astrophysical Journal* **212**: pp. L107–L111 (1977).

[28] C. W. F. Everitt, ed., *The Final Report on NASA Grant 05-020-019 to Perform a Gyro Test of General Relativity in a Satellite and Develop Associated Control Technology,* (Stanford University, Palo Alto, California, July, 1977).

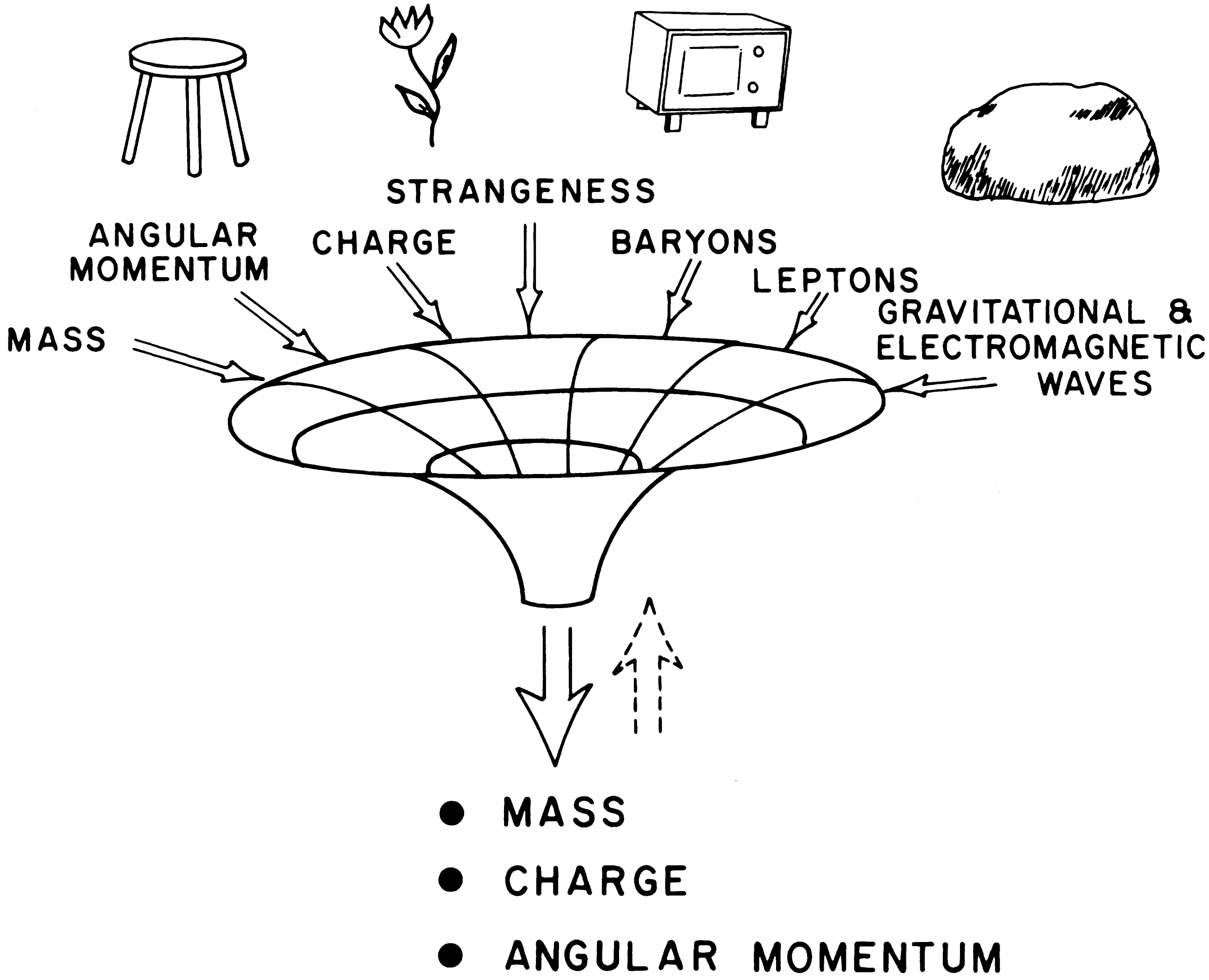

FIG. 6. "A black hole has no hair"; it extinguishes all particularities of everything that falls in.

dius of the Sun; 40 "lightseconds") for a black hole of 4 million solar masses, the mass of the black hole believed to be at the center of the Milky Way; and 14 "lighthours" for the five billion solar mass black hole attributed to the galaxy M87.

The time required to fall from the horizon to the point of crunch, the place where conditions become singular, is also directly proportional to the mass, a sixth of a millisecond for a black hole of ten solar masses, twenty-one hours for a black hole of five billion solar masses.

Time goes slowly near a black hole. There is a close-at-hand illustration of the mechanism. Put an atomic clock on the surface of the Earth. Let it send signals up an elevator shaft to a point 22.5 meters higher. The interval from pulse to pulse is found to be greater than the interval between tick and tick of an identical clock located at the top of the shaft. In this sense the clock closer to the Earth's surface goes slower than the clock further away.[29] Likewise a clock somehow suspended close above a black hole will send signals to a faraway observer, equipped with an identical clock, which will have a spacing between tick and tick which can be two times or five times or a hundred times that of this faraway fiducial standard. In this sense time can be made to go arbitrarily slowly if one is willing to live arbitrarily close to a black hole.

Can time be made to go backward? The great logician Kurt Gödel was passionately interested to the day of his death in a model of the universe—today

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[29] R. V. Pound and G. A. Rebka, "Apparent weight of photons," *Physical Review Letters* **4** (1960): pp. 337–341; R. V. Pound and J. L. Snider, "Effect of gravity on nuclear resonance," *Physical Review Letters* **13** (1964): pp. 539–540; R. V. Pound and J. L. Snider, "Effect of gravity on gamma radiation", *Physical Review B* **140** (1965): pp. 788–803.

unacceptable—that admitted "closed time-like world lines."[30]

In another context I received one day a long distance telephone call from a distinguished Washington lawyer.

> "My wife and I have lost our only child, our twelve-year-old son. Without him nothing has any meaning for us. We're willing to run any risk, pay any price, do whatever it takes to be transported back in time to his company. We have heard that black holes exist and that time goes backward in the neighborhood of a black hole. Is that true?"

I had to tell him, "I'm so sorry; no."

VERY SMALL AND VERY LARGE BLACK HOLES

No one has been able to propose any astrophysical process which will collapse a mass smaller than the Sun to a black hole.[31] However, the primordial chaos of the big bang at the time the universe came into being might offer conditions propitious for the creation of mini black holes. An Arctic ice island ten meters thick and ten km square, if compacted into a black hole, would be as small as the nucleus of an atom. Such a black hole, coming from space and passing by us at a distance of some meters, would give us all a violent jolt. It would also create a localized earthquake as it bored its way down into the Earth.

At still smaller dimensions, of the order of the so-called "Planck length," $\sim 1.6 \times 10^{-33}$ cm, twenty powers of ten smaller than the atomic nucleus, no one sees any way to escape a mechanism which all the time and everywhere is continually bringing into being black holes and wiping them out, annihilating and creating, creating and annihilating. The mechanism is "quantum fluctuations in the geometry of space." To the transatlantic passenger flying above it, the ocean appears smooth. When the traveler's plane has dropped in altitude to a hundred meters above the surface he sees the waves. When he is in the lifeboat he sees the foam forming and breaking, breaking and forming. Space, smooth at the everyday level, and smooth even at distances comparable to atoms, atomic nuclei and elementary particles, is predicted at still smaller distances to show a foamlike structure[32] (fig. 7).

If the fantastically small Planck distance represents the smallest level at which it makes sense to talk of black holes, what is the largest distance? If the universe, as Einstein envisaged it, is closed, then the present period of expansion will be followed by a period of contraction. It will bring together not only existing stars but also existing black holes. They will undergo successive amalgamations, becoming larger at each step. They will all come together in the final crunch of the universe itself.

Is the universe then also to be regarded as a black hole? No. It is characteristic of a black hole to be surrounded by an "outside." One can put a planet in orbit around the black hole and from the time of revolution in that orbit tell the mass of the center of attraction. The universe, however, if closed has no outside. There is no circumferential highway for the planet. The mass of a closed universe has no meaning. With no mass and no outside the universe is very different from a black hole.

BIG BANG AND COLLAPSE: PROXIMITY WITHOUT PROXIMITY

Can one see in more detail the relation between a typical black hole and the universe? Nothing is more misleading in one's first thinking about big bang and collapse than the notion that everything starts from a "point." The rectangle in figure 8 provides a symbolic representation of spacetime. The big bang is indicated by the heavy horizontal line at the lower right; the big crunch by the upper heavy horizontal line. In the intervening spacetime, the "we" and the "they" are two galaxies, today separated by billions of light years, which nevertheless began in all the compactness of the same big bang. We, today, ten billion years down the road, receive light rays from them, given off when they were only one billion years old. However, they at that time had not yet received a single light ray from us. This is the sense in which objects that began close together did not begin close together.

Likewise, two galaxies (not shown), followed in time up to the moment when they coalesce in the big

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[30] K. Gödel, "An example of a new type of cosmological solution of Einstein's field equations of gravitation," *Reviews of Modern Physics* **21** (1949): pp. 447–450; K. Gödel, "Rotating universes in general relativity theory," *Proc. of the 1950 International Congress of Mathematicians* **1** (1950): p. 175; W. Kundt, "Trägheitsbahnen in einen von Gödel angegebenen Kosmologischen Modell," *Zeitschrift für Physik* **145** (1956): pp. 611–620. In such a universe one could as an old man return to the moment of the birth of one's father or grandfather or some more remote ancestor. Gödel's model universe demanded that the universe everywhere partake of a "preferred rotation." This requirement is decisively contradicted by what one has since learned about random sense of rotation of faraway galaxies: D. L. Hawley, "The distribution of orientations of galaxies, with special attention to selection effects," doctoral dissertation, Princeton University, 1972; D. L. Hawley and P. J. E. Peebles, "Distribution of observed orientations of galaxies," *Astronomical Journal* **80** (1975): pp. 477–491.

[31] The difficulties of bringing about collapse of a less than solar mass also mean that no feasible way offers itself to make a "gravitational bomb"; see for example fig. 16, p. 81 in Harrison *et al.*, footnote 12.

[32] J. A. Wheeler, "On the nature of quantum geometrodynamics," *Annals of Physics* **2**: pp. 604–614 (1957); G. W. Gibbons and S. W. Hawking, "Action integrals and partition functions in quantum gravity," *Physical Review* **D15**: pp. 2752–2757 (1977); S. W. Hawking, D. N. Page and C. N. Pope, "The propagation of particles in spacetime foam," *Physics Letters* **B86**: pp. 175–178 (1979); M. J. Perry, "Gravitational Instantons" (preprint, Princeton University, Princeton, N.J., 1980; to appear in *Annals of Mathematics Studies on Differential Geometry*).

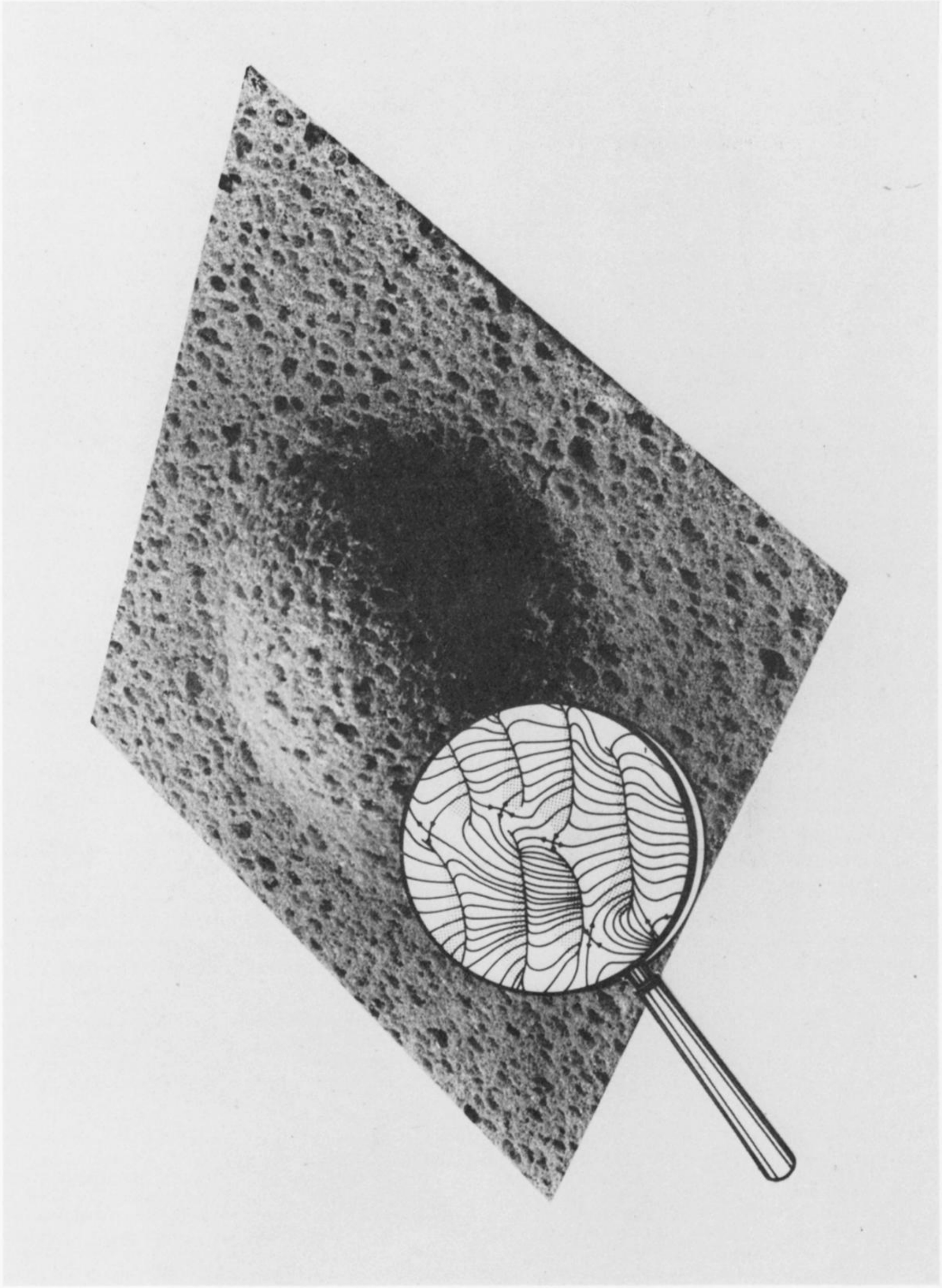

FIG. 7. Symbolic representation of the foam-like structure expected for space at the Planck scale of distances.

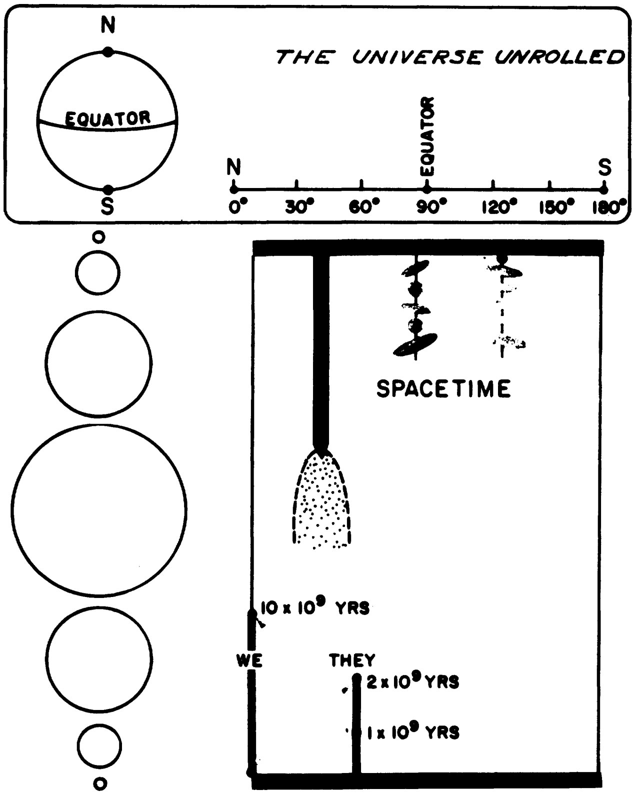

FIG. 8. Unity of the black hole singularity and the singularity of a final crunch. Lower left, the 3-sphere universe symbolized by a circle which, reading upwards, starts small, grows larger, reaches a maximum dimension, contracts and collapses. Above, this circle unrolled to provide an angular measure (0° to 180°) of the separation from point to point. Lower right, spacetime diagram with this angular measure of distance running horizontally and time running vertically upward. The heavy black "stalactite hanging from the roof" symbolizes a black hole formed by the collapse of the indicated cloud of dust. The ellipses symbolize the "mixmaster oscillations" predicted in the geometry in the final phase of approach to the big crunch (horizontal heavy line).

crunch, are not able to signal back and forth to each other despite this final proximity.

These features of cosmology prepare one little for what happens when a black hole (symbolized by the heavy vertical line) is added to the story. The dotted region in the diagram represents a cloud of dust starting large and shrinking as time goes on, at first slowly, then more and more rapidly, until it collapses to a black hole (the spike). The singularity of that black hole, seen in these terms, is part and parcel of the final cosmological singularity itself. From one point of view it is a point. What coalesces to it coalesces to the same point as does all the other matter in the universe. From another point of view, these "separate" points of coalescence are separate: in the last microsecond before collapse there is no possibility for back and forth signaling between separate bits of matter about to be obliterated. That is the sense in which proximity is not proximity.

TIME ENDS

Beyond all these caveats and details stands the central feature in a closed universe: Time ends.

The ending of time at the singular center of a black hole and the ending of time in the cosmological big crunch itself are not two separate endings but features of one and the same ending, one and the same gate of time. The other gate of time is the big bang.

The black hole thus provides us with a here and now "experimental model" for the collapse foreseen for the Einstein closed universe itself. In the buying of a house, the purchase money is put into escrow with the title guaranty company until the final transfer to the seller at the moment of purchase. In a black hole, matter is put into escrow beyond hope of recovery before its final complete obliteration. No wonder the black hole refuses to give anyone outside the slightest indication of what went in apart from those immaterial measures of total mass, total electric charge and total angular momentum!

Of number of particles that went in not a trace is left, if present physics is safe as guide. Not the slightest possibility is evident, even in principle, to distinguish between three black holes of the same mass, charge and angular momentum, the first made from particles, the second made from antiparticles and the third made primarily from pure radiation. This circumstance deprives us of all possibility to count or even define particle number at the end and compare it with the starting count. In this sense the laws of conservation of particle number are not violated; they are transcended.

THE STAIRCASE OF LAW AND LAW TRANSCENDED

Figure 9 pictures the development of physics as a staircase. Each step symbolizes a new law or discovery. Each riser marks the attainment of conditions so extreme as to overcome the usefulness of that law, or transcend it.

Archimedes, discovering how to measure density, could regard it as a constant of nature. However, later ages achieved pressures great enough to bring about measurable alterations in density. The concept of valence brought into order the major facts of chemistry, but today we know we have only to go to very high temperatures to outrun traditional valence considerations. Later came the discovery that every atomic nucleus admits rigid classification by its charge number and its mass number; but the advent of nuclear transmutations destroyed that rigidity. The laws of conservation of baryon number and lepton number are indispensable in accounting for the wealth of experience in elementary particle physics but they have no application in black hole physics. There they are not violated, but transcended.

In the end can we not at least say that the black hole has mass and therefore mass-energy? And does not the law of conservation of energy stand up against

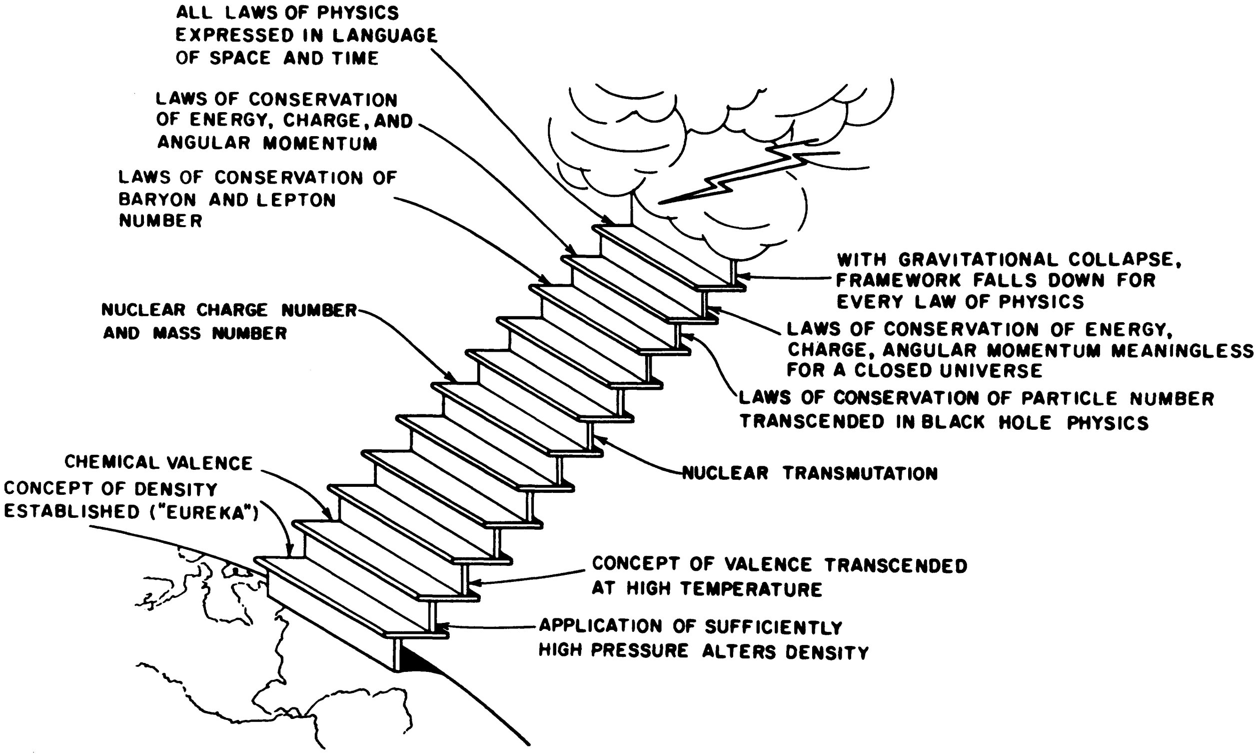

FIG. 9. The staircase of law and law transcended. Each step symbolizes the discovery of a new regularity or constancy of nature; each riser, the discovery of a technical means or a natural condition so extreme as to overcome or transcend that regularity.

arbitrarily extreme conditions? In an asymptotically flat space, yes; in a closed universe, no. In a closed universe the idea of "total mass-energy"—and with it the law of conservation of energy—lose all meaning and application.

At the head of the stairs there is a last footstep of law and a final riser of law transcended. There is no law of physics that does not require "space" and "time" for its statement. Obliterated in gravitational collapse, however, is not only matter, but the space and time that envelop that matter. With that collapse the very framework falls down for anything one ever called a law of physics.

Einstein's general relativity gives not the slightest evidence whatsoever for a before before the big bang or an after after collapse. For law no other possibility is evident but that it must fade out of existence at the one bound of time and come into being at the other.[33] Law cannot stand engraved on a tablet of stone for all eternity. Of this strangeness of science we have for symbol the staircase; and for central lesson, "Time ends."

So far as we can see we lead a one-time-only life in a one-time-only universe. Each day is all the more precious because we will not see it again.

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[33] For a fuller statement of this theme see the articles cited in footnote (2).