Relativistic Astrophysics at Caltech: 1923-1969

by Kip S. Thorne

A report on Caltech's contributions to theoretical studies of relativistic cosmology and stellar evolution

One of the greatest triumphs of pre-twentieth century physics was Newton's law of gravitational "action at a distance," $F = Gm_1m_2/r^2$. This simple law explained the complicated motions of the planets and their satellites in the solar system, as well as the effects of gravity in earthbound laboratories. Despite its success, by 1905 it was known to be wrong.

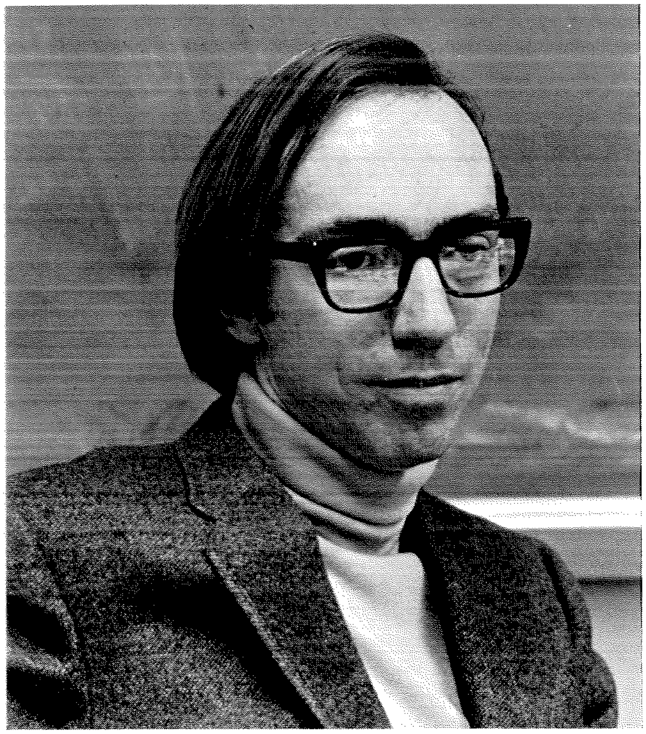
The disproof of Newton's law came from both experiment and theory. On the experimental side, it could not account for an excess precession of the perihelion of Mercury's elliptical orbit amounting to 43 seconds of arc per century. On the theoretical side, it was incompatible with Einstein's special theory of relativity—the theory which Einstein developed in 1905 to describe the relationships between observers moving with large relative velocities.

Between 1905 and 1915 Einstein worked hard to create a theory of gravity that would be compatible with special relativity and would explain all the experimental facts, including the perihelion shift of Mercury. In 1915 his efforts bore fruit, and he published his general theory of relativity.

General relativity theory and Newton's law of gravity are entirely different conceptually. According to general relativity, space and time make up a four-dimensional "space" (or *manifold*) called spacetime, which is curved. The curvature of spacetime is produced by its material content (galaxies, stars, planets, people). Experimentally, the curvature of spacetime shows up as gravity. In effect, gravity and spacetime curvature are one and the same thing.

Despite its completely revolutionary formulation, general relativity gives the same predictions as Newtonian theory when applied to the solar system, the galaxy, and the structures of normal stars—or almost the same predictions. General relativity always predicts tiny "post-Newtonian" corrections to the Newtonian results. In the solar system these corrections amount to less than one part in a million of the dominant Newtonian behavior; nevertheless, a number of them have been detected. These include the perihelion shift of the planet Mercury and of the asteroid Icarus, the gravitational redshift of light and of gamma rays, the gravitational deflection of starlight and of quasar radio waves, and an anomalous time delay for radar signals bounced off planets.

Although relativistic gravitational effects are miniscule in the solar system, in normal stars, and in the galaxy, they are of crucial importance elsewhere in the universe: (1) The large-scale structure and evolution of the universe itself (*cosmology*) is governed by relativistic effects; Newtonian theory is useless there. (2) Highly relativistic objects may be responsible for quasars and for explosions in the nuclei of galaxies. (3) Neutron stars, with relativistic deviations from Newtonian gravity of up to 200 percent, are probably formed in supernova explosions and are probably the recently discovered pulsating radio



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sources which have come to be known as *pulsars*.

The study of systems such as these, with highly relativistic gravitational fields, is called *relativistic astrophysics*. Research in relativistic astrophysics is a major activity in the Kellogg Laboratory today. In fact, Kellogg's involvement in this research goes back to the infancy of Einstein's theory itself.

In 1915 Einstein had no idea that relativistic gravitational effects might one day prove crucial for finite astronomical objects such as pulsars and quasars. However, he did know that they would be crucial for cosmology, so this was where he turned his attention as soon as he had formulated general relativity. He soon discovered, to his dismay, that general relativity does not admit static cosmological models. The universe would have to be expanding or contracting, and this was in contradiction to the beliefs of the day. In semi-panic at this discovery, Einstein modified his theory in 1917 to include a cosmological constant, which would produce a pressure to keep the universe static.

Not so repelled by the idea of a dynamical universe was a young man named H. P. Robertson. From 1918 to 1923 Robertson was a student at the University of Washington, where he developed an interest in general relativity. In 1923 he came to Caltech to study for the PhD under Harry Bateman and Paul Epstein. His PhD thesis in 1925, "On the Dynamical Space-Times which Contain a Conformal Euclidean 3-Space," was one of the first theoretical studies to take seriously the possibility that the universe might be dynamical. (The metric for the geometry of such dynamical spacetimes has been called the "Robertson-Walker metric" ever since.)

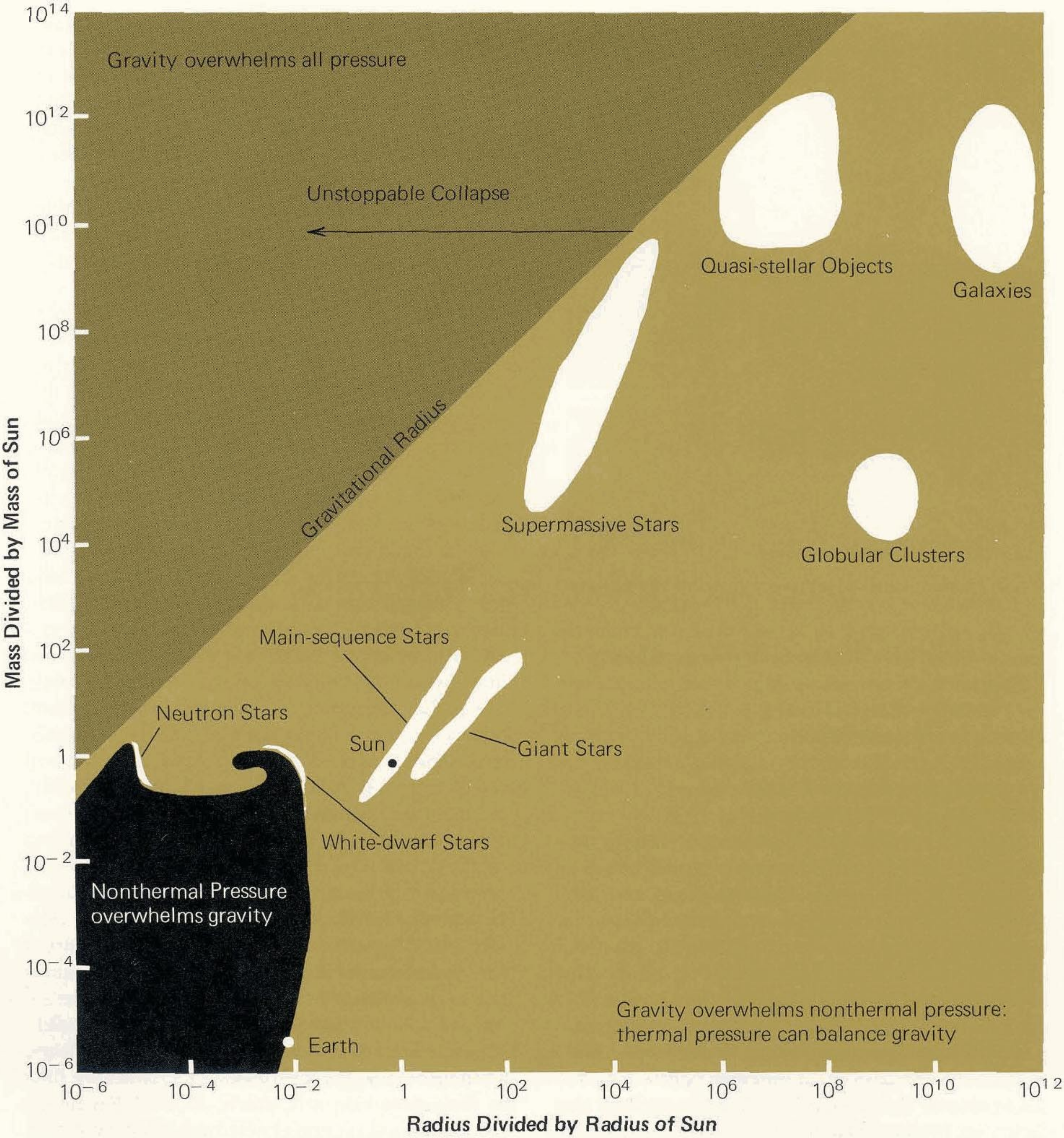
In 1930 the Caltech astronomer Edwin Hubble rocked the foundations of cosmology by showing that the universe is *not* static; it is expanding. Suddenly Robertson's work was of the utmost relevance.

Although Robertson had left Caltech for Princeton in 1929, this did not leave Caltech bereft of relativistic astrophysicists. The discoveries being made at Mount Wilson in 1930 were too exciting to be ignored by theorists. Richard Chace Tolman, who had come to Caltech in 1923, and J. Robert Oppenheimer, who had arrived in 1927, made fundamental contributions to theoretical cosmology and relativistic astrophysics throughout the subsequent decade. (Tolman's contributions were immortalized in his classic book *Relativity, Thermodynamics, and Cosmology*; Oppenheimer's contributions, we shall return to shortly.)

The old guard of the Kellogg faculty still tell the tales of those exciting days: Tolman, "Oppie," and Charlie Lauritsen were inseparable friends. When they got together in the lab or under the arcades, the conversation ranged all the way from Charlie's newest experimental results to Tolman's latest ideas on cosmology and Oppenheimer's latest calculations on neutron stars.

After World War II, in 1948, Oppenheimer left Caltech for Princeton, Robertson returned from Princeton to Caltech, and Tolman died.

The 1950's were slow years for relativistic astrophysics throughout the world. Caltech's 200-inch Hale telescope on Mount Palomar went into operation, and with it Allan Sandage and others produced significant improvements in the cosmological data. But there were no great surprises, no revolutions. On the theoretical side at Caltech, Richard Feynman made significant progress toward the quantization of general relativity; Jon Mathews, with his student Philip Peters, developed the theory of gravitational waves from binary-star systems; and Mathews, with Robert Kraft and Jesse Greenstein, investigated a particular binary system (WZ Sagitae) for which the energy losses due to gravitational radiation might eventually be detectable. In the fifties the action was elsewhere in physics and astronomy; so Robertson,



Mass-radius diagram depicting the dimensions of various astrophysical objects: Relativistic astrophysics is concerned with objects near their gravitational radii—collapsing objects, neutron stars, supermassive stars, perhaps quasi-stellar objects, and the universe as a whole (which sits near its gravitational radius, far off in the diagram in the upper right). Whether quasi-stellar objects actually lie in the relativistic region is not clear.

Sandage, Feynman, and Mathews dabbled only occasionally in general relativity and relativistic astrophysics.

All of this changed quite suddenly in the early sixties. On the cosmological scale (10^{10} light years), groups at Bell Laboratories and Princeton discovered the cosmic microwave radiation. On a smaller scale (10^6 to 10^9 light years from the earth), Caltech's astronomers discovered quasars and explosions in the nuclei of galaxies. On the theoretical front, work on stellar evolution—much of it performed in Kellogg Laboratory—began to suggest strongly that neutron stars and perhaps even "black holes" might be formed at the endpoint of stellar evolution. Finally, in 1967 came the discovery of pulsars, which seems to have verified the existence of neutron stars.

In response to these discoveries, the Kellogg Laboratory has had a vigorous program in theoretical relativistic astrophysics since 1963. Research during this period has concentrated on cosmology, on quasars and the nuclei of galaxies, and on the endpoint of stellar evolution.

COSMOLOGY

The cosmic microwave radiation has revolutionized cosmology. The observations, carried out with radiometers in the wavelength range from one millimeter to one meter, are just what one would expect if the earth were enclosed in a box whose walls had a temperature of 2.7 degrees Kelvin. Of course, nobody believes that such a box is out there. Rather, nearly everyone believes that the radiation was formed in the big-bang creation of the universe ten billion years ago and that it has bathed the entire universe ever since. The original temperature of the radiation was billions of degrees, but the expansion of the universe has cooled it by now to 2.7 degrees.

From the present temperature of the radiation and the mean density of matter in the universe, we can (in principle) reconstruct the entire history of the universe. This is possible if we assume that, on a large-scale average, the universe is homogeneous and isotropic. Much of the effort of our Caltech group since 1963 has concentrated on the following reconstruction of the history of the universe:

1. The formation of primordial helium in the big bang, when the universe was only a few minutes old, has been calculated in Kellogg by William A. Fowler and Robert V. Wagoner, and at Princeton by P. J. E. Peebles, who is working in our group this year. They have found that approximately 25 percent of the mass of the primordial matter should have been converted from hydrogen to helium in the big bang—a figure much higher than astronomers had previously believed. Most subsequent astronomical observations have tended to agree with this new figure.

2. Peebles has been delineating the processes by which globular clusters and galaxies probably condensed out of the interstellar medium when the universe was several hundred million years old.

3. Vahé Petrosian, a research fellow in Kellogg, has been studying the effects of the cosmological constant on the history of the universe.

Into all these studies goes the assumption that the universe is homogeneous and isotropic, when one ignores the lumpiness due to clumping of matter into galaxies and clusters of galaxies. How good is this assumption? The cosmic microwave radiation again is the key to the answer: Its intensity is measured to be isotropic to within 0.1 percent. To gauge the significance of such measurements, Kenneth Jacobs and I have investigated anisotropic, general-relativistic cosmological models. The result of comparing the Princeton measurements of isotropy with our theory is that the universe, on a large-scale average, is now expanding at the same rate in all directions to an accuracy of one part in ten thousand or better. This amounts to a three-thousand-fold improvement on our previous knowledge of the isotropy of the expansion! The microwave isotropy also implies an impressive degree of large-scale homogeneity for the universe.

QUASARS AND EXPLOSIONS IN THE NUCLEI OF GALAXIES

The energy released in quasars and in explosions in the nuclei of galaxies is so enormous that theoreticians have been forced to invoke esoteric processes to explain it. Thus far none of the explanations has been successful enough to gain wide acceptance, so work on the theory continues along many fronts. One of the first proposals, made in our laboratory by William A. Fowler and Fred Hoyle in 1963, was based on violent activities of a supermassive star—a star of more than a million solar masses. (No stars more massive than 100 solar masses have ever been observed, but Fowler and Hoyle present cogent arguments why supermassive stars might form in the nuclei of galaxies or in quasars.) A key facet of supermassive stars is an instability against gravitational collapse due to general-relativistic effects. This relativistic instability was discovered independently in 1963 by Feynman at Caltech and by S. Chandrasekhar at the University of Chicago, and it has played an important role in the subsequent theory of supermassive stars. Today the supermassive-star theory is still a vigorous competitor in the quasar marketplace; it is particularly popular in the Soviet Union.

Another 1963 proposal to explain the quasar energies was gravitational collapse, which general relativity predicts should destroy supermassive stars and other massive objects when the relativistic instability sets in. Gravitational collapse was first discovered and studied as a general-relativistic phenomenon by J. Robert Oppenheimer and his student, Hartland Snyder, at Caltech and the University of California in 1939. From then until 1963 gravitational collapse remained in the backs of peoples' minds as a vaguely possible phenomenon in astrophysics. In 1963, however, with the discovery of quasars and of the relativistic instabilities in stars, it came roaring into the focus of attention. In principle, collapse could convert 100 percent of the mass of a body into high-energy radiation and particles; this was an implication of Oppenheimer's work. Is this the key to the quasar energy? Perhaps so, according to 1963 calculations by Curtis Michel in our laboratory; probably not, according to subsequent, more refined calculations by others in the laboratory; quite uncertain, according to current thought.

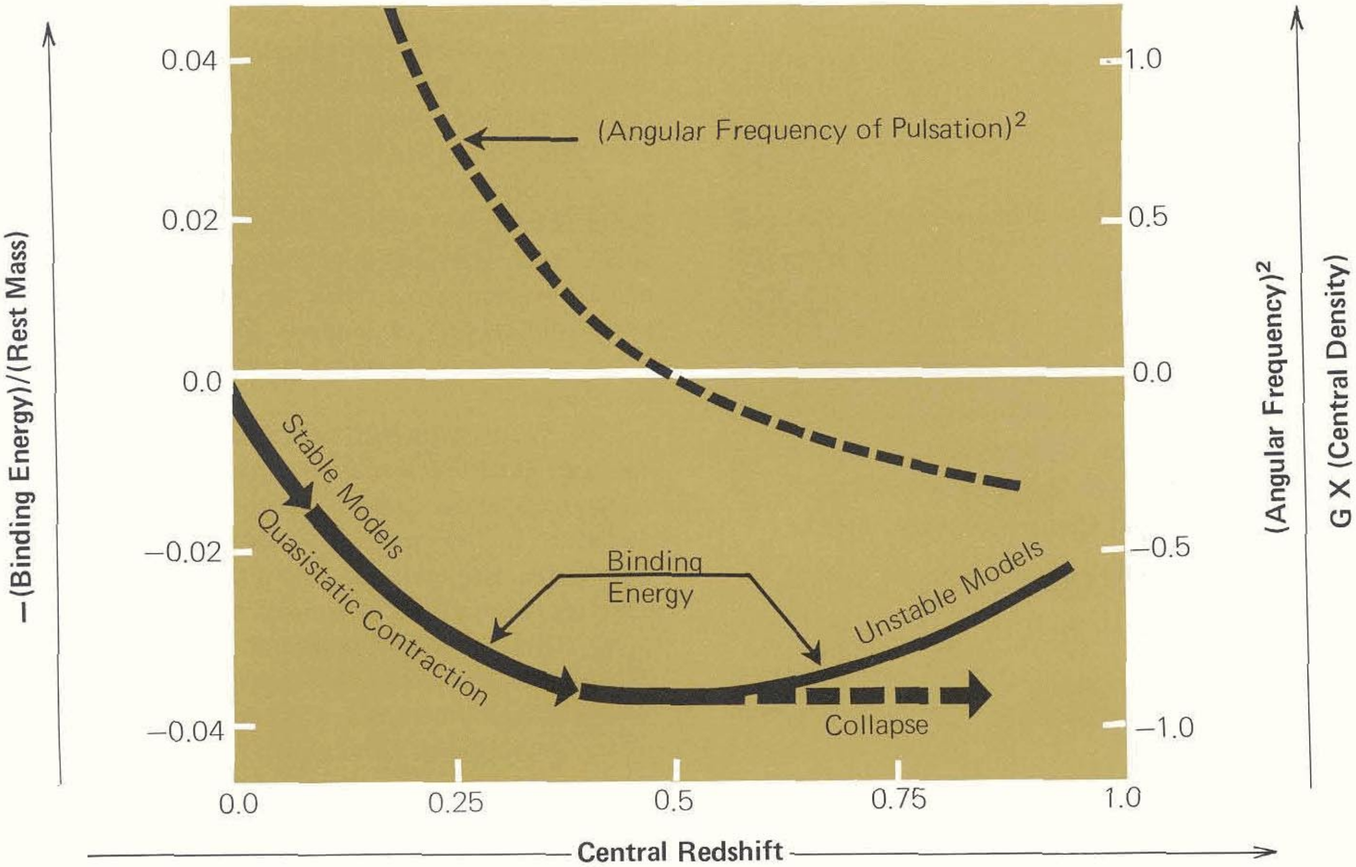
Before we can say anything definitive about the role of gravitational collapse, we must understand it better. All pre-1968, general-relativistic studies of it assumed spherical symmetry. But spherical symmetry may be a terribly bad approximation for realistic collapse. For example, in the spherical case no energy, or light, or anything else can escape from a star after it has collapsed through its "gravitational radius"; the star leaves behind a gravitating black hole in space. "But," prominent relativity theorists have argued, "perhaps small deviations from spherical symmetry will completely change this; perhaps there will be no black hole; perhaps it will always be possible to get the energy of collapse back out."

To evaluate this and other speculations requires extensive mathematical studies of general relativity theory. Such studies are now under way in our group and elsewhere. Preliminary results obtained by Richard Price, one of our students, constitute a strong case against the above speculation. It appears very likely that nonspherical collapse is qualitatively like spherical collapse. The results of this study and others like it will be the foundation for future applications of the theory of collapse to astronomical phenomena.

A third proposal to explain the energy outputs of quasars and of galactic nuclei relies upon star-star collisions and supernova explosions in superdense star clusters (clusters with more than a billion stars per cubic light year). A variant of this idea, due to Fowler and Hoyle at Caltech in 1967, makes the cluster so dense that general-relativistic effects produce a huge gravitational redshift of the spectral lines emitted by matter near its center. This could account for most of the redshift of the light from quasars, permitting them to be much nearer the earth than we had previously thought (no cosmological shift needed!), and partially alleviating the difficulties with the apparently huge energy output.

Whether this theory is right or not, it has suddenly forced astrophysicists to realize that relativistic effects could be important in clusters of stars as well as in individual stars. What would those relativistic effects be, besides the gravitational redshift? Some preliminary answers had been given, before the work of Fowler and Hoyle in 1967, by Zel'dovich and Podurets in Moscow (1965) and by Fackerell in Australia (1966). But these groups were unaware that their work was anything more than a mathematical exercise—i.e., that it could be significant for astrophysics—so they did not pursue it far. Here was a major subject for theoretical research, virtually untouched, and of potentially great significance for astrophysics. James Ipser, one of our students, launched eagerly into it in the spring of 1967; a year later Fackerell came from Australia to work with Ipser, and in the summer of 1969 Donald Lynden-Bell—an expert on Newtonian star clusters—will come from England for a year, in part to work with Ipser and Fackerell.

One of the most exciting results of our star-cluster work is that clusters, like individual stars, are subject to a relativistic instability. As time goes on, star-star collisions and stellar evaporation cause a cluster to contract to higher and higher density. When its density becomes so large that the redshifts of photons emitted from its center are $\Delta\lambda/\lambda = 0.5$, the cluster begins to collapse. All of its stars spiral in toward the center, leaving behind a black hole. At least this is the case for spherical clusters whose stars have isotropic velocity distributions. If it is also true for more general clusters, then the Hoyle-Fowler star-cluster model cannot produce redshifts as large as those observed for some quasars ($\Delta\lambda/\lambda$ up to 2.4).



The structure and evolution of a relativistic star cluster with a truncated Maxwellian velocity distribution. The cluster initially contracts slowly, becoming more and more tightly bound. When the binding reaches a maximum, relativistic collapse begins, and all the stars spiral inward through the gravitational radius.

Nevertheless, collisions and collapses in relativistic star clusters might still be a key to the outbursts of quasars, and to explosions in some galaxies.

ENDPOINT OF STELLAR EVOLUTION

Theoretical work in the 1930's by Oppenheimer and his students at Caltech and the University of California, and by Chandrasekhar, then in Cambridge, England, suggested that three types of objects should be the endpoints of stellar evolution: white-dwarf stars (radius $\sim$ 6000 kilometers, density $\sim 10^6$ g/cm^3), neutron stars (radius $\sim$ 10 kilometers, density $\sim 10^{14}$ g/cm^3), and black holes (radius $\sim$ 5 kilometers). Subsequent theoretical work in the late 1950's and early 1960's firmed up these predictions. Particularly important was the theoretical work on supernova explosions by Hoyle, Fowler, and Geoffrey and Margaret Burbidge, and subsequent work by others, which predicted that neutron stars should be formed in supernova explosions.

By 1963 observational astronomers, particularly Jesse Greenstein at Caltech, had produced extensive data on white-dwarf stars, data which meshed well with the theory. But nobody had ever found any observational evidence for the existence of neutron stars or black holes. Nevertheless, the theoretical case for neutron stars was so compelling that the group here in Kellogg Laboratory and John Wheeler's group in Princeton (of which I was then a member) embarked on vigorous studies of them.

What observational handle might one get on neutron stars? This was the crucial question. One possibility, of course, was thermal radiation from the surface of a neutron star. Because of the extreme smallness of its surface area (a few hundred square miles) a neutron star would be very dim. But it might not be hopelessly dim. How hot should a neutron star's surface be? A few million degrees, if the star was only a few thousand years old, according to calculations by Hong-Yee Chiu in New York City in 1963. In this case, young neutron stars should produce primarily x-rays, not light! Several months after

$G_2{}^2 = R_2{}^2 - \frac{1}{2}R$: Computer Output

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2U     2L
 5.0E-1*AL*EP**2.0*H2*X**(-1.0)*FMCEXP(-ALAM)*FMCDIF(ALAM,(X,1))-
 5.0E-1*AL*EP**2.0*H2*X**(-1.0)*FMCEXP(-ALAM)*FMCDIF(ANU,(X,1))+
 2.5E-1*AL*EP**2.0*H2*FMCEXP(-ALAM)*FMCDIF(ALAM,(X,1))*FMCDIF(ANU,(
 X,1))-2.5E-1*AL*EP**2.0*H2*FMCEXP(-ALAM)*FMCDIF(ANU,(X,1))**2.0-
 5.0E-1*AL*EP**2.0*H2*FMCEXP(-ALAM)*FMCDIF(ANU,(X,2))+AL*EP**2.0*X
 **(-1.0)*FMCEXP(-ALAM)*FMCDIF(AK,(X,1))-5.0E-1*AL*EP**2.0*X**(-1.0
 )*FMCEXP(-ALAM)*FMCDIF(HO,(X,1))-5.0E-1*AL*EP**2.0*X**(-1.0)*
 FMCEXP(-ALAM)*FMCDIF(H2,(X,1))+AL*EP**2.0*X**(-1.0)*FMCEXP(-ALAM-
 ANU)*FMCDIF(H1,(T,1))-2.5E-1*AL*EP**2.0*FMCEXP(-ALAM)*FMCDIF(AK,(X
 ,1))*FMCDIF(ALAM,(X,1))+2.5E-1*AL*EP**2.0*FMCEXP(-ALAM)*FMCDIF(AK,
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 FMCDIF(H2,(X,1))-5.0E-1*AL*EP**2.0*FMCEXP(-ALAM)*FMCDIF(HO,(X,2))-
 5.0E-1*AL*EP**2.0*FMCEXP(-ALAM-ANU)*FMCDIF(ALAM,(X,1))*FMCDIF(H1,(
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 5.0E-1*AL*EP**2.0*FMCEXP(-ANU)*FMCDIF(AK,(T,2))-5.0E-1*AL*EP**2.0*
 FMCEXP(-ANU)*FMCDIF(H2,(T,2))-5.0E-1*EP**2.0*HO*X**(-2.0)*FMCSIN(Y
 )**(-1.0)*FMCCOS(Y)*FMCDIF(AL,(Y,1))+5.0E-1*EP**2.0*H2*X**(-2.0)*
 FMCSIN(Y)**(-1.0)*FMCCOS(Y)*FMCDIF(AL,(Y,1))+5.0E-1*X**(-1.0)*
 FMCEXP(-ALAM)*FMCDIF(ALAM,(X,1))-5.0E-1*X**(-1.0)*FMCEXP(-ALAM)*
 FMCDIF(ANU,(X,1))+2.5E-1*FMCEXP(-ALAM)*FMCDIF(ALAM,(X,1))*FMCDIF(
 ANU,(X,1))-2.5E-1*FMCEXP(-ALAM)*FMCDIF(ANU,(X,1))**2.0-5.0E-1*
 FMCEXP(-ALAM)*FMCDIF(ANU,(X,2))$
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$G_2{}^2 = R_2{}^2 - \frac{1}{2}R$: People notation

$$
\begin{aligned}
&\tfrac{1}{2}P_\ell \xi H_2 r^{-1} e^{-\lambda}\frac{d\lambda}{dr} - \tfrac{1}{2}P_\ell \xi H_2 r^{-1} e^{-\lambda}\frac{d\nu}{dr} + \tfrac{1}{4}P_\ell \xi H_2 e^{-\lambda}\frac{d\lambda}{dr}\frac{d\nu}{dr} - \tfrac{1}{4}P_\ell \xi H_2 e^{-\lambda}\left(\frac{d\nu}{dr}\right)^2 \\
&-\tfrac{1}{2}P_\ell \xi H_2 e^{-\lambda}\frac{d^2\nu}{dr^2} + P_\ell \xi r^{-1} e^{-\lambda}\frac{\partial K}{\partial r} - \tfrac{1}{2}P_\ell \xi r^{-1} e^{-\lambda}\frac{\partial H_0}{\partial r} - \tfrac{1}{2}P_\ell \xi r^{-1} e^{-\lambda}\frac{\partial H_2}{\partial r} \\
&+P_\ell \xi r^{-1} e^{-\lambda-\nu}\frac{\partial H_1}{\partial t} - \tfrac{1}{4}P_\ell \xi e^{-\lambda}\frac{\partial K}{\partial r}\frac{d\lambda}{dr} + \tfrac{1}{4}P_\ell \xi e^{-\lambda}\frac{\partial K}{\partial r}\frac{d\nu}{dr} + \tfrac{1}{2}P_\ell \xi e^{-\lambda}\frac{\partial^2 K}{\partial r^2} \\
&+\tfrac{1}{4}P_\ell \xi e^{-\lambda}\frac{d\lambda}{dr}\frac{\partial H_0}{\partial r} - \tfrac{1}{2}P_\ell \xi e^{-\lambda}\frac{d\nu}{dr}\frac{\partial H_0}{\partial r} - \tfrac{1}{4}P_\ell \xi e^{-\lambda}\frac{d\nu}{dr}\frac{\partial H_2}{\partial r} - \tfrac{1}{2}P_\ell \xi e^{-\lambda}\frac{\partial^2 H_0}{\partial r^2} \\
&-\tfrac{1}{2}P_\ell \xi e^{-\lambda-\nu}\frac{d\lambda}{dr}\frac{\partial H_1}{\partial t} + P_\ell \xi e^{-\lambda-\nu}\frac{\partial^2 H_1}{\partial t\,\partial r} - \tfrac{1}{2}P_\ell \xi e^{-\nu}\frac{\partial^2 K}{\partial t^2} - \tfrac{1}{2}P_\ell \xi e^{-\nu}\frac{\partial^2 H_2}{\partial t^2} \\
&-\tfrac{1}{2}\xi H_0 r^{-2}\cot\theta\,\frac{dP_\ell}{d\theta} + \tfrac{1}{2}\xi H_2 r^{-2}\cot\theta\,\frac{dP_\ell}{d\theta} \\
&+\tfrac{1}{2}r^{-1}e^{-\lambda}\frac{d\nu}{dr} + \tfrac{1}{4}e^{-\lambda}\frac{d\lambda}{dr}\frac{d\nu}{dr} - \tfrac{1}{4}e^{-\lambda}\left(\frac{d\nu}{dr}\right)^2 - \tfrac{1}{2}e^{-\lambda}\frac{d^2\nu}{dr^2}
\end{aligned}
$$

Calculations in general relativity involve tedious manipulations of algebraic expressions—since 1967 performed on computers. Above is one component of the Einstein tensor for the simple problem of a star in nonradial pulsation, produced by the computer and translated into "people language."

Chiu's prediction came the discovery of x-ray "stars" by telescopes flown in rockets. Great excitement ensued for about a year, until two new developments cooled the enthusiasm: John Bahcall and Richard Wolf in Kellogg Laboratory recalculated the cooling of neutron stars due to the emission of neutrinos, and they found a much more rapid cooling than had Chiu—too rapid to leave sufficient x-rays to account for the observations. At the same time, refinements in the observations revealed that some of the x-ray sources were much larger than neutron stars and had nonthermal spectra.

In what other ways might neutron stars make themselves known? Any observational features would have to result from the release of stored energy. The energy could be stored in heat (already investigated by 1963), vibrations (unstudied in 1963), or rotation (also unstudied). Thus it was that, at Princeton in 1964, we turned our attention to the theory of the pulsation and rotation of neutron stars.

Because relativistic deviations from Newtonian theory are as great as 200 percent in some neutron-star models, we had to use general relativity, in its full nonlinear glory, in this work. By the time I came to Caltech in 1965, David Meltzer, a student of mine, and I had worked out the properties of radial pulsations of neutron stars. Since then James Hartle (UC Santa Barbara), Alfonso Compolattaro (UC Irvine), Richard Price (a student in our laboratory), and I have worked together to develop the general relativistic theory of neutron stars which rotate, which pulsate nonradially, and which emit gravitational waves.

This five-year project, now essentially complete, has been great fun; and it has produced a payoff for astronomy, which came much sooner than we had dreamed. In February 1968 radio astronomers in Cambridge, England, announced their discovery of a class of pulsating radio sources with intervals between pulses of about one second. The only kinds of objects which could have characteristic periods so short are highly compact white dwarfs, where relativistic gravitational effects are important, and neutron stars, where relativity is crucial. And the only reasonable "clock mechanisms" for governing the pulses are the pulsation and the rotation of such stars. Consequently, our theory of the pulsation and rotation of relativistic stars has become a foundation on which models of pulsars are constructed these days.

As a result of the most recent observations, it seems highly likely that the pulsars are rotating, magnetic neutron stars.

A second payoff for our studies is the recent detection, by Joseph Weber (University of Maryland), of vibrations in an isolated aluminum cylinder, vibrations which may well be due to bursts of gravitational waves from neutron stars in the process of formation. If Weber has indeed detected gravitational waves, then our work on the emission of such waves by pulsating neutron stars may play an important role in the interpretation of his data.

Despite the crucial role played by relativistic gravitational effects in cosmology, pulsars, and (perhaps) quasars, we do not know for certain yet whether general relativity is the correct relativistic theory of gravity. Fortunately, solar-system experiments using, among other things, JPL space probes should give the answer within the next five or ten years. To facilitate the planning for these experiments, the Caltech relativistic-astrophysics group may turn its attention next to the theory of relativistic celestial mechanics.