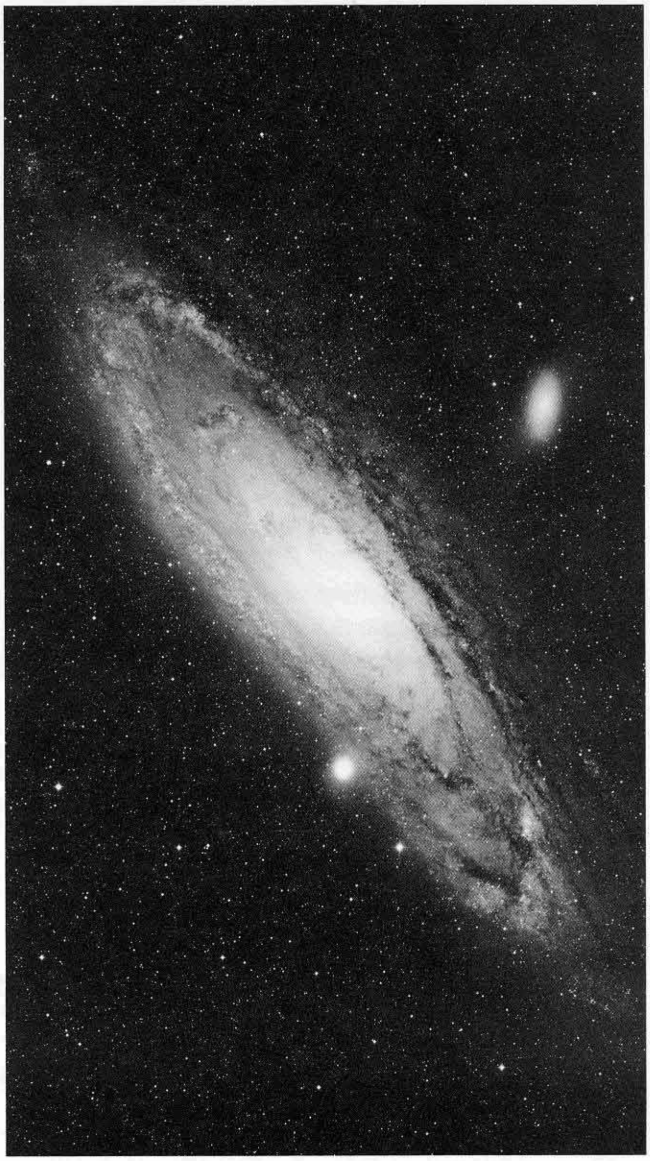
Probing the Universe:

Big Bang, Black Holes, and Gravitational Waves

by KIP S. THORNE



The galaxy Andromeda, as seen through the 48-inch Schmidt telescope.

Astronomical research in recent decades has brought considerable understanding of the universe around us. We know, of course, that the universe was created in a "big-bang" explosion some 12 billion years ago. We know that the primordial gas, expanding outward from that explosion, condensed to form galaxies such as the great Andromeda galaxy shown here. We know that those galactic condensations occurred when the universe was roughly one billion years old, some 10 to 20 billion years ago.

We know that each such galaxy is made of some 100 billion stars, that each star has a finite lifetime, that stars are continually being born and continually dying. We know that stars are born in great clouds of dust and molecular gas. We know that when they die, they die in remarkable ways, producing, for example, white dwarfs—objects the size of the earth but with masses like that of the sun and densities of some tons per cubic inch.

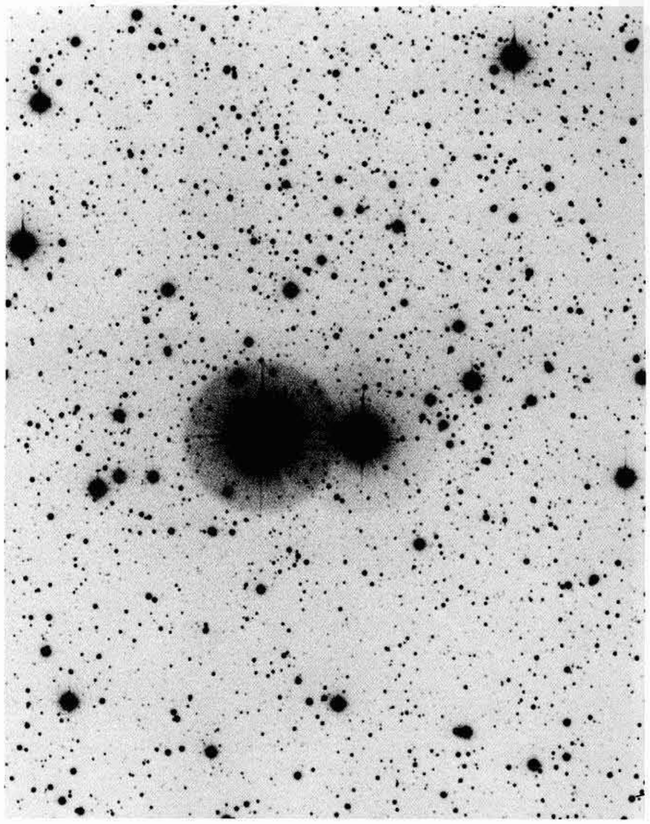
We know that other, more massive stars die to form neutron stars—objects only 20 kilometers across but weighing as much as the sun and having densities of a billion tons per cubic inch. We know that stars also die to form black holes—objects which are veritable edges of our universe in confined regions; objects down which things can fall, but out of which nothing can come; objects which seem more fantastic than anything conceived of by science fiction writers, but which Einstein's theory of relativity says must exist or Einstein is wrong.

In talking about the future of astronomy and things one hopes to discover, I could go from one topic to another, lighting your minds up with excitement for the many possibilities. But I have chosen instead to focus on just one small area—an area which to me is exciting, not least because, as a by-product of our inquisitive search, it promises to produce new technological innovations. This area is the challenge of understanding the deaths of stars, and particularly understanding black holes.

One can understand what a black hole is by imagining the fate of a very massive star—one perhaps 10 times as large as the sun—which has exhausted its nuclear fuel, and can no longer replenish the internal heat that supports it against the pull of its own gravity. Gravity then pulls the star inward upon itself into catastrophic collapse. Now, imagine a fleet of asbestos-covered rocket ships, all lined up on launching pads that float in the gaseous stellar surface. These rockets are to monitor the progress of the collapse by measuring the "escape velocity" from the star's surface —the velocity a rocket must achieve in its initial few moments of blasting, in order to successfully escape from the star's gravitational pull.

The first rocket, launched before the collapse begins, requires an escape velocity of, let us say, 100 kilometers per second. Later, as the star collapses, the gravitational pull at its surface becomes stronger because of Newton's inverse square law for gravity. Hence, a rocket launched when the star has collapsed to one quarter its original size requires an escape velocity of not 100, but 200 kilometers per second. And ultimately, when the star's circumference has shrunk to roughly 100 kilometers, the escape velocity grows larger than the speed of light. Now, we all know that nothing can travel faster than light—not light, not radio waves, not particles, not rocket ships, not anything. So the star at that point, with a circumference of 100 kilometers, cuts itself off from the rest of the universe and leaves behind something that can only be called a "black hole in space."

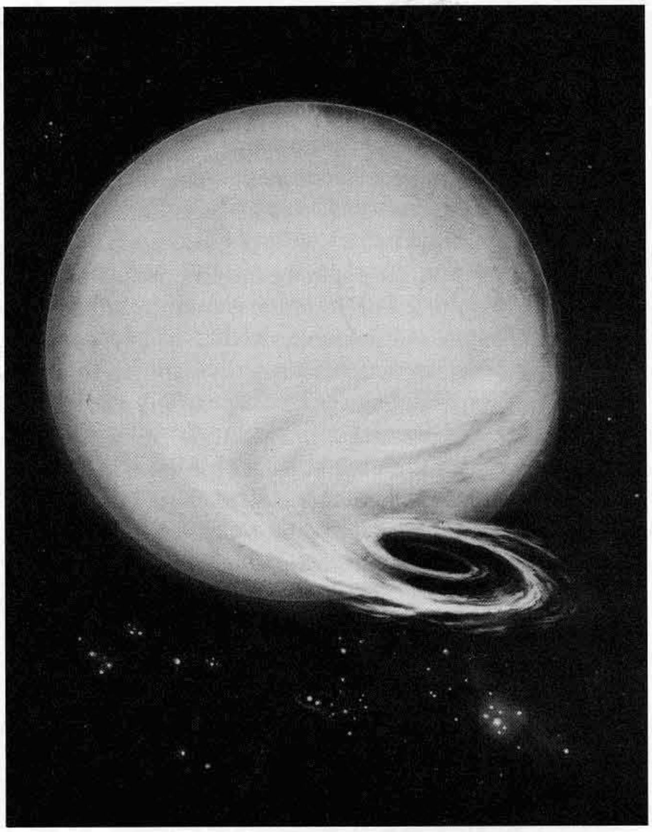
This kind of picture of a black hole—as simply a boundary with roughly a 100-kilometer circumference, out of which nothing can come—is only a shadow of what a black hole really is. When one tries to analyze black holes theoretically, using the mathematics of Einstein's General Theory of Relativity, one finds that a black hole in fact is gravity creating gravity. It is curvature of space creating further curvature of space. It is as though space itself were a gigantic rubber membrane, a membrane so massive in the neighborhood of the hole that it curves itself up so strongly as to prevent anything from ever getting out. The challenge for the astronomer in the near future is to study this extreme curvature of space observationally, to see if Einstein's predictions about it are correct.



Star field centered on the star HDE226868 (Cygnus X-1), photographed by Jerry Kristian with the 200-inch Hale telescope.

We are now at a point where astronomers are perhaps 80 percent sure that a black hole has been discovered. There are other good black hole candidates in the sky, but the very best one is an object shown above as photographed by Jerry Kristian of the Hale Observatories with the 200-inch telescope. The very brightest thing you see in the picture is a star whose number is HDE226868. The fact that it even has a number means that it's a very bright star indeed, so bright that if it were only 40 times more luminous, you would begin to be able to see it with your naked eye.

This star is an object from which we receive not only light but also X rays and radio waves. When its X rays were discovered, it was given the name Cygnus X-1. Thanks to the collective efforts of dozens of astronomers using X-ray telescopes on board satellites (primarily Ricardo Giacconi and his group at Harvard with the UHURU satellite), and thanks to radio and optical telescopes on the ground, one deduces that this



An artist's conception of Cygnus X-1.

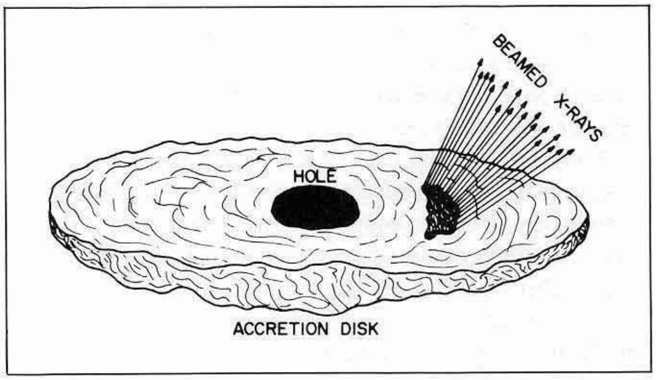
star probably has a black hole in orbit around it.

If we could get up closer (we are roughly 10 thousand light years away), we would probably see something like the artist's conception of this object reproduced above. The big thing in the middle of the picture is a very massive normal star; and down in the center of that swirl in the lower right-hand corner lives a black hole, tiny in size but with nearly as much gravity as the big star. The black hole is close enough to the star that its gravity pulls gas off the star. The gas is swirling down into the neighborhood of the black hole; and as it swirls, it heats up, becoming so hot before it falls into the hole that it emits X rays more intensely than any other kind of radiation—X rays which astronomers on earth can study and try to use to deduce the properties of the black hole.

The theory of this "accretion" of gas onto black holes has been developed by several groups in the Soviet Union, in England, and in the United States. Their theory suggests that centrifugal forces will throw the infalling gas into a thin disk, shown below, something like the rings of Saturn. The swirling gas in the disk may form hot spots, my Russian friend Rashid Sunyaev has suggested; and the X rays that come off of such hot spots would likely be beamed. As a hot spot orbits around and around the black hole, its X-ray beam should precess around and around in the sky above the hole. An earth-orbiting X-ray telescope should receive a burst of X rays each time the beam sweeps past it. If you could discover such bursts and time them in the manner that the radio astronomer times the bursts of radio waves from a pulsar, then you would be studying the orbital characteristics of things in motion around a black hole. Those orbital characteristics would tell you very directly the properties of the strongly curved space near the hole. When I say "near the hole," I should emphasize that roughly 50 percent of the X-ray energy comes from within less than 12 black-hole radii of the hole. So one has real hope of studying Einstein's conception of curved space near this strange object.

The bottleneck in searching for such bursts in Cygnus X-1 is their great rapidity, perhaps 200 per second, and the small X-ray flux seen at the earth—not much more than one photon per 1000 square centimeters per burst. Hints of such bursts show up in rocket-flight data taken by Dr. Richard Rothschild and his group at the Goddard Space Flight Center, but their telescope did not have enough collecting area to give definitive results, and other existing telescopes are even less useful.

Fortunately, the search for such bursts should be



A disk of gas accreting onto a black hole, and a hot spot on the hole that beams its X rays in a manner suggested by Rashid Sunyaev.

revolutionized this year by the HEAO-A X-ray satellite which was launched on August 12. On board the satellite are two banks of X-ray detectors constructed by Dr. Herbert Friedman and his colleagues at the Naval Research Laboratories. One bank of Friedman's detectors will total 2 thousand square centimeters; the other, 12 thousand; and they will have microsecond and millisecond time resolution. They should be able to really pin down the existence or nonexistence of the predicted bursts. And if the bursts are found, careful timing of them may give the definitive test of whether Cygnus X-1 is a black hole, and may help us to understand whether Einstein was right about the curvature of space around black holes. That's something we can expect and hope for over the next year or two or three.

Now let me turn attention to the more distant future —to the challenge of observing the birth of a black hole, of probing deep down inside a collapsing star and watching the curvature of space vibrate as the black hole is being formed. One can't hope to observe such things with light, X rays, or radio waves. There's too much obscuring matter in the surrounding stellar envelope. There are only two ways to look cleanly through the surrounding envelope. The best way, it seems at present, is to use gravitational waves rather than electromagnetic waves. The second possible way is to use neutrinos, which also escape relatively unimpeded from the interior of the star.

A gravitational wave is a ripple in the curvature of spacetime that is ejected from the black hole in its birth throes and then propagates toward the earth with the speed of light. Now the phrase "a ripple in the curvature of spacetime" sounds nice, but it doesn't really mean much to most people. What this ripple of curvature actually does is jiggle neighboring inertial reference frames relative to each other. And since matter initially at rest likes to remain at rest relative to its inertial frame, the wave also jiggles adjacent pieces of matter relative to each other. Just as the jiggling in an electromagnetic wave is transverse to the direction of propagation, so it is also in a gravitational wave. But whereas an electromagnetic wave jiggles only charged particles, a gravitational wave jiggles inertial frames—and thereby jiggles all forms of matter and energy.

Professor Joseph Weber of the University of Maryland has built a pioneering apparatus to search for gravitational waves from the birth throes of black holes and neutron stars. He took a one-ton aluminum bar and glued piezoelectric crystals around its middle. The bar at all times was ringing in its fundamental mode like a bell, due to its finite temperature; and as it rang, it squeezed the piezoelectric crystals in and out, producing electric voltages which when amplified told Weber the amplitude of vibration of his bar. If a strong gravitational wave, propagating roughly perpendicular to the bar, were to hit it, the wave would push the bar's ends first in and then out, driving a change in the bar's oscillation amplitude.

Now, gravitational waves have extremely small cross-sections to interact with matter. So whether the wave came up through the bottom of the earth or down from above made no difference. There was essentially no attenuation in the earth. Any wave coming in from any direction roughly perpendicular to the bar could drive its vibrations.

Professor Weber's piezoelectric crystals were able to measure end-to-end vibrations of the bar with amplitudes of the order of 10^{-14} centimeters. That's a tenth the diameter of the nucleus of an atom. You say how can one possibly ever measure things that are vibrating with a fraction of the diameter of the nucleus of an atom? The answer, of course, is that here one is not measuring a vibration of a single atom; rather, in the bar there are some 10^{29} atoms and 10^{29} atomic nuclei, and they're all doing this vibration at once. Of course, each one individually is doing a lot of other things. But the fact that they all do this particular vibration coherently, and that you have so many of them, enables you to talk meaningfully and with high precision about measuring the total bulk motion of the vibrating bar to a precision of a fraction of the diameter of the nucleus of an atom.

Now, Professor Weber thought at one time that he might be seeing gravitational-wave bursts arriving at the earth several times per day. But subsequent experiments have indicated that probably he was not. This is rather fortunate from the viewpoint of astrophysicists like me, because it was very difficult for us to dream up sources of gravitational waves so strong that they would produce a 10^{-14} centimeter vibration of Weber's bar.

The kinds of sources that we think one should search for are the birth throes of neutron stars and black holes—but not birth throes in our own galaxy, because they probably occur here only once every 30 years; rather birth throes out in more distant galaxies, say at a distance of 100 million light years, at which point you would have a dozen birth throes per year.

Such black-hole and neutron-star births should produce end-to-end vibrations in a Weber-type bar about three thousand times smaller than current detectors can measure. That's down in the neighborhood of 3×10^{-19} centimeters. So the challenge is to monitor the vibrations of that kind of a bar to a precision of 3×10^{-19} centimeters, an improvement of a factor of three thousand over current technology in amplitude, a factor of ten million in energy—and energy is really the more reasonable way to think about it. We need a factor of ten million improvement.

Well, this looks hopeless at first sight. But, thanks in large measure to Professor Vladimir Braginsky of Moscow University, we have before us a number of possibilities for making the required improvements.

The first of these possibilities, suggested by Braginsky six years ago, is to use instead of an amorphous metal bar as the detector, a monocrystal of sapphire or some other material. Professor Weber at Maryland and Professor David Douglass at the University of Rochester are now experimenting with sapphire and silicon crystals, and find them very promising. Weber's, Douglass's and Braginsky's present crystals weigh only one to five kilograms; but they hope ultimately to use crystals of 100 kilograms and perhaps more. Of course, such massive crystals are not found in nature; they are grown from the melt industrially. At present you can go out and buy a 10-kilogram crystal of sapphire, off the shelf, for a few thousand dollars.

The key point about such crystals is that, if you cool them to low temperatures, they have very high "Q's" compared to amorphous metal bars; and the more you cool them, the higher the Q goes. A very high Q means that, if you hit the bar, its ringing will die out only very slowly. And if the bar is sitting there ringing because of its finite temperature, its ringing will be so "pure" that its amplitude will change due to internal forces only very, very slowly.

This means that if a gravitational wave comes by and produces a quick change in the ringing amplitude, you can say that the change was almost certainly not produced by internal frictional or thermal forces, and this means, therefore, that such a change might well have been due to a gravitational wave.

The original Weber bars had Q's of about 100,000, which means they rang for 100,000 cycles before the bar changed its amplitude substantially. For comparison, one of Braginsky's sapphire crystals, cooled to about 4 degrees Kelvin temperature and not very well polished as yet, has achieved a Q of 10^{10}, which is a factor of 100,000 better than amorphous metal bars.

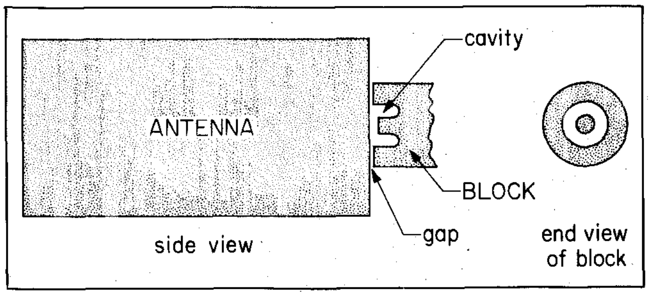
The cooling of gravitational-wave antennas is a second major innovation now under way. It is being pushed primarily by Professor William Fairbank's group at Stanford University and by Professor William Hamilton of Louisiana State University. They plan ultimately to cool massive bars down to millidegree temperatures. At such temperatures, and with improved polishing, sapphire or silicon crystals may well achieve Q's in the range of 10^{12} to 10^{14}. Such a crystal, if hit, would ring strongly for 3 to 300 years before it died out. And such a crystal, in thermal equilibrium, would have only a few thousand quanta of vibration in its fundamental mode—yes, we know that the vibrations of a big crystal must be quantized, just like the energy levels of an atom. And with such a crystal, at millidegree temperatures, you would have to wait roughly one minute for internal thermal forces to add or remove a single quantum! If you can monitor the number of quanta of vibration in the crystal with a time resolution of a minute; and if you see in that time a change by say 10 quanta, you can say that something very strange has happened, that something really hit the bar, and perhaps it was a gravity wave.

So that is the challenge: to take a 100-kilogram bar with a few thousand quanta of vibration in it, to regard it as a quantum-mechanical system—the most massive quantum-mechanical system that people have ever worked with—and to observe quantum changes in its vibrations. If you can do that, then you can study the births of black holes out to very great distances in the universe—out to such distances that you'll have many black-hole births per year. Conceivably, by the end of the century you might "see" all the way out to the edge of the universe. Of course, the question is how do you do it.

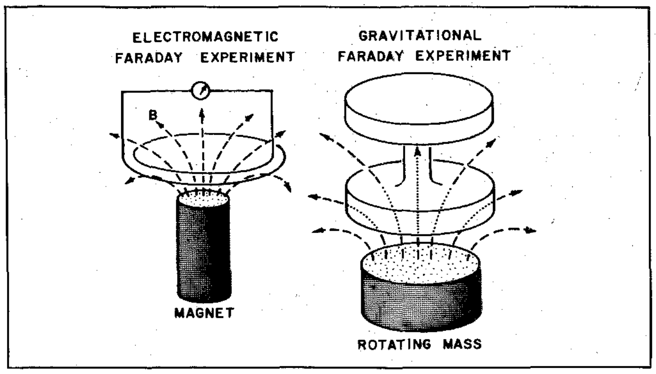
There is a very serious difficulty along the way which will take great effort to overcome; and that effort is likely to "drive" technology, producing important fallout elsewhere. To help in describing this difficulty one of the methods now being developed to measure the vibrations of a bar is shown below. This method was suggested by John Dick at Caltech six years ago, and is now being pursued by Braginsky in Moscow. You have an antenna or bar vibrating away with an amplitude of roughly 10^{-17} centimeters, and you want to measure changes in its amplitude of a few times 10^{-19} centimeters, corresponding to the creation or removal of a few quanta of vibration. At one face of the antenna you have a block of niobium, just barely not touching the bar.

The niobium block has a little reentrant cavity machined out of it, and it is properly polished and surface-treated to make it a good superconductor. The face of the bar is coated with niobium; and the bar, plus the block, forms an enclosed cavity which you drive into electromagnetic oscillation at microwave frequencies. The mechanically vibrating bar and the electromagnetically vibrating cavity form a coupled system. If you can measure the number of quanta of electromagnetic excitation in the cavity, then you can infer from it the number of quanta of mechanical oscillation of the bar. That's very helpful, because with modern technology it is much easier to measure electromagnetic oscillations than mechanical oscillations.

But now comes the difficulty—a difficulty first pointed out by Braginsky four years ago, but much clarified by Robin Giffard at Stanford last year. With any kind of sensor that one has nowadays for looking at microwave vibrations in a cavity, the best one can do is to measure the number, N, of quanta of excitation to a precision of the square root of N. If the cavity is excited with a million quanta, one can measure it to a precision of at best ±1000 quanta. That's not good enough. If that's the best you can do, then there is only very marginal hope of seeing gravity waves from black-hole births at a distance of 100 million light years, which is how far you have to look in order to see one black hole born say every month. You might be able to see that far, but you'll have to be very lucky. And there is no hope at all of seeing farther.



The use of a microwave cavity to measure the vibrations of a gravitational-wave antenna.



Left: Faraday's 1831 electromagnetic induction experiment. Right: a possible gravitational induction experiment by which one might hope to detect magnetic-type gravitational fields.

Braginsky has given the name "quantum-non-demolition sensor" to any device that can measure the number N of quanta in an oscillator more accurately than $\sqrt{N}$. This is because the key to the failure of all standard sensors is that they disturb the oscillator—that is, they demolish the quantum state in which it resides —in the process of making their measurements. The problem, then, is to devise a quantum-non-demolition sensor. And if one can do so, and build it, one may be able to use it as a foundation for innovations elsewhere in technology. For example, such a non-demolition sensor might become the key element in a new generation of amplifiers, with far lower noise temperatures than the best amplifiers that exist today.

Quantum-non-demolition sensors can surely exist in principle. Theorists have no trouble inventing idealized ones. But to invent one that really works in practice is something else. Recently Braginsky in Moscow and Bill Unruh at the University of British Columbia have invented promising devices; but it will take a long time—perhaps five years—to construct working models. Meanwhile, there is a search for better, simpler designs.

Even without quantum-non-demolition sensors, one can hope to do some wonderful gravitation experiments with high-Q sapphire or silicon crystals. The figure above shows an example that Braginsky in Moscow and Carlton Caves and I at Caltech have been thinking about together.

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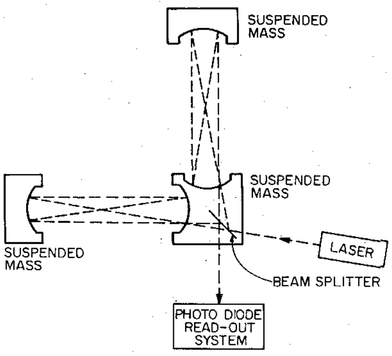
As background for this experiment, I must tell you that, according to Einstein, gravity must have associated with itself "magnetic-type" forces as well as "electric-type" forces. All past gravity experiments have measured only electric-type forces—forces that are independent of the velocity of one's apparatus. A challenge for the near future is to detect magnetic-type gravity, gravitational forces that depend linearly on the velocity of one's apparatus. In a sense, gravitation research today is where electromagnetic research was at the beginning of the 19th century.

One way to make gravity catch up with electromagnetism would be to perform a gravitational analog of Michael Faraday's famous induction experiment. In his 1831 experiment Faraday moved a magnet up and down near a coil of wire. As the magnetic flux linking the coil changed, it induced an electromotive force (EMF) around the wire, causing electrical current to flow and to be measured by the device at the top of the picture.

Over on the right-hand side of the picture we see the gravitational analog of Faraday's experiment. It is an experiment that might be done five years or so from now. The rapidly rotating mass produces a magnetic-type gravitational field—something nobody has ever seen before, but something that might be useful for technology in the distant future. Above the rotating mass is a sapphire crystal that has been machined into a dumbbell shape so that its period of torsional vibration is one one-hundredth of a second. The rotating mass is moved up and down one hundred times per second; and as it moves, there is an oscillation of the flux of its magnetic-type gravitational field which threads the lower half of the dumbbell. The changing flux induces a gravitational "EMF" in the crystal. In other words, it induces an oscillating, circular gravitational force in the bottom part of the crystal; and that force, oscillating away for about one week, drives an amplitude change of perhaps 10^{-18} centimeters in the crystal's torsional oscillations.



A multipass Michelson interferometer for use in detecting gravitational waves.

One can hope to measure such a change with standard sensors. A quantum-non-demolition device is unnecessary if the experiment is carefully designed. And having made such a measurement, one could not only say unequivocally that magnetic-type gravity exists; one could also determine whether Einstein's general relativity correctly predicts the amount of magnetic-type gravity produced by the rotating mass.

Let me return now to gravitational radiation, and describe for you two other detection techniques that are currently under development. These make use of the fact that the larger the detector is, the larger will be the signal produced by a gravitational wave, and the less need there will be for a quantum-non-demolition sensor.

One technique, being developed by Ray Weiss at MIT, Ronald Drever in Glasgow, and H. Billing in Munich, makes use of a "multipass Michelson interferometer." Four mirrors are suspended by pendula below an overhead support, to form two arms of an interferometer, as shown in the picture above. (In practice one would probably use eight mirrors and four arms.) The laser beam is split in two; and the two beams are bounced back and forth between the mirrors of the two arms. After roughly 1000 bounces—with each bounce making a distinct and separate spot on a mirror—the beams are recombined and examined for interference.

The swinging frequencies of the pendula are far below the frequencies of the searched-for gravitational waves; so waves hitting the device drive the mirrors back and forth as though they were "free" masses. Moreover, because gravitational waves have spin 2 (according to Einstein), they will drive the mirrors of one arm toward each other while driving the mirrors of the other arm apart. The resulting oscillations of the arm lengths will produce oscillations of the interference pattern of the combined beams.

This device has the advantage that, because of the 1000 bounces of the laser beam, its effective length is 1000 times the length of the arms. Nevertheless, to detect waves from stellar collapses 100 million light years away, one will need arm lengths of several kilometers or more; and one will need enormous isolation from seismic vibrations. It is not at all clear whether such size and isolation can be achieved on earth. One might have to deploy the device in space. More modest prototype devices with arm lengths of several meters are now under construction and should operate successfully on earth with sensitivities better than current Weber-type bars.

I turn now to gravitational-wave detectors and gravitational-wave sources with sizes far larger than the ones described above. Our photograph of Andromeda on page 17 illustrates the fact that most galaxies of stars are very quiescent systems, beautifully calm and quiet. However, occasionally one finds a galaxy such as M82 (right) in which gigantic explosions are occurring in the nucleus. It seems likely that those explosions are either generated by huge black holes, or produce huge black holes as by-products. By "huge" I mean black holes weighing a million to a billion times the mass of the sun.

The challenge for astronomers is to measure the gravitational waves produced by the birth of such a gigantic black hole as that. A way in which to do this—a method that is under active investigation by Hugo Wahlquist, Frank Estabrook, and others at JPL—is by means of spacecraft tracking. One sends out highly monochromatic radio waves from the Goldstone tracking antenna; one receives them at a spacecraft in deep interplanetary space; the spacecraft retransmits them back to earth; and the tracking antenna receives them and measures their net Doppler shift, their change in frequency. From that Doppler shift one infers the velocity of the spacecraft relative to the earth.

Now, when a burst of gravity waves passes through the solar system, it induces very tiny motions of the spacecraft and the earth relative to each other. If you can measure those motions, using the Doppler tracking data from the earth-spacecraft link, then you can learn from them the details of the gravitational wave, and try to infer information about the birth of a huge black hole in the nucleus of a very, very distant galaxy.

What does this require? It requires making measurements of the velocity of the spacecraft to a precision of something like one part in 10^{16} of the velocity of light, which means you need clocks on the earth that are stable to about one part in 10^{16} over times of the order of minutes to hours. And in fact, those kinds of clocks are on the way. We are accustomed to thinking of atomic clocks, particularly the hydrogen maser, as being the best clocks around. But the record for the best clock is not held by the hydrogen maser any longer; it's held by a "classical" clock—a "super-conducting cavity stabilized oscillator," which is nothing but the same kind of little microwave cavity I was talking about before, in connection with detection of the gravitational waves from the death of a normal star. The ticking mechanism of such a clock is the microwave oscillations in its cavity.


The galaxy M82, photographed by Alan Sandage with the 200-inch telescope.

Professor John Turneaure at Stanford has built such a clock and has achieved a stability of 6 parts in 10^{16}, which is four times better than the best hydrogen maser. And Turneaure expects soon to achieve one part in 10^{16} or better, which is what is required for our spacecraft tracking project. With further improvements on the way in Moscow and elsewhere, we can hope for one part in 10^{17} in five years or so. And if other parts of the Doppler tracking system can be cleaned up, which is one thing JPL is currently looking at, then we can have real hope in 10 to 15 years of seeing gravity waves from the births of gigantic holes out at the very edge of the universe, waves emitted back when galaxies were very young and their explosions with black-hole births were perhaps most frequent.

Not all of the future efforts and progress in cosmology and relativistic astrophysics will come from experimental work. Theoreticians can hope to make some contributions too. Let me fire up your imagination with the following example:

When we talk about the birth of the universe in a big-bang explosion some 12 billion years ago, the normal man in the street always wants to know what caused the explosion; where did it come from. And up until now we physicists have had to say, not only do we fail to know the answer; we don't even know how to ask the question in such a form that there is any hope of learning the answer. However, within the last three years hints about how to ask the question have come from the work of Dr. Stephen Hawking in Britain, and also of Leonard Parker and James Hartle in the United States and of Yakov Borisovich Zel'dovich in the Soviet Union. Thanks to them and others, we can begin to hope to understand the birth of the universe.

It appears that very strong gravitational fields—such as those that occur in the centers of black holes but not typically at their surfaces, and such as those that had to occur in the initial state of the universe when the big-bang explosion began—are able to create matter. In fact they have to create matter. In their presence the "vacuum" is unstable against production of matter. And one is in the position now of beginning to do calculations to see just what kinds of matter and how much had to be produced by the initial intense gravitational fields at the birth of the universe. Moreover, there are glimmers of hope that from such calculations we may learn the precise form in which the matter had to come out, that we may learn why there are more baryons than antibaryons in the universe, and why the ration of photons to baryons in the universe is 10^9.

My colleagues label me an optimist when I speak, as I have here, of future goals and trends in relativistic astrophysics. However, to me the achievements of the past two decades—the creation and development of X-ray astronomy and long baseline radio interferometry, the construction of unmanned observatories in space, the discoveries of quasars, pulsars, neutron stars, cosmic microwave radiation from the big bang, and perhaps black holes—these achievements justify high goals for the future, strong optimism, and intense work. ☐