# The Last Three Minutes

## *Computing the shape of gravitational waves to come*

By IVARS PETERSON

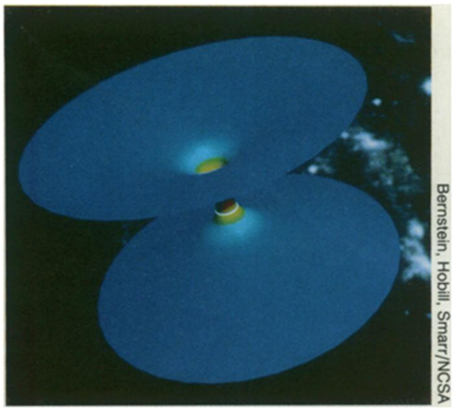
Locked by gravity into a madly whirling partnership, two neutron stars inexorably spiral inward to a final, frenzied embrace. As the partners draw closer together, they swing around each other faster and faster. Each star tugs on the other, stretching it more and more out of shape. Finally, they touch and coalesce.

According to Einstein's general theory of relativity, this suicidal stellar dance also creates extreme distortions in the geometry of the space surrounding the stars. Theorists believe these spacetime disturbances travel outward as gravitational waves that imperceptibly jostle any objects in their paths. During the last few minutes before coalescence, the waves may be strong enough that sensitive detectors on Earth, millions of light-years away, have a chance of reading their distinctive signatures.

By the end of this century, researchers hope to have in operation a network of instruments for detecting gravitational waves produced by spiraling pairs of neutron stars and of black holes. Construction of the two detectors for the Laser Interferometer Gravitational Wave Observatory (LIGO) is set to start later this year in Livingston, La., and Hanford, Wash. (SN: 2/29/92, p.134). Scientists in France and Italy are collaborating on a third detector, VIRGO, to be built near Pisa, Italy.

To help tease out a gravitational wave signal hidden in the noise that will inevitably rattle these detectors, theoretical physicists have now taken on the challenging task of predicting what the signals will look like. Initial results from one of these efforts suggest that physicists may glean more information from these signals than they had previously thought possible.

In the May 17 PHYSICAL REVIEW LETTERS, researchers from the California Institute of Technology in Pasadena and Northwestern University in Evanston, Ill., contend that it may be possible not only to detect gravitational waves but also to infer the masses of the spiraling partners responsible for the waves. Analysis of signals emanating from distant pairs may also lead to new estimates of crucial cosmological parameters, including the expansion rate of the universe and its density.


Bernstein, Hobill, Smarr/NCSA

*Spacetime curved by presence of black hole.*

This new research effort "is changing our understanding of these [gravitational] waves," Caltech's Curt Cutler and his collaborators report. "The waveforms will be far more complex and carry more information than has been expected."

What success these theorists may have hinges on the formidable task of solving the equations underlying the general theory of relativity. The equations describe a physical force, gravity, in terms of geometry – variations in the curvature of space and time.

According to this theory, massive bodies, such as neutron stars and black holes, warp spacetime significantly. Moreover, if a massive body abruptly changes its motion or mass, spacetime in its vicinity undergoes a corresponding convulsion, which travels outward as a gravitational wave.

Although weak, these waves should create detectable gravitational disturbances when they reach Earth. Moreover, different sources of gravitational waves should generate unique wave shapes that can be deciphered to characterize the sources and identify their type.

"We need to know what these signals will look like," says Kip S. Thorne of Caltech. This means using theory to derive a family of gravitational wave "templates" to serve as guides for processing the noisy data obtained at the LIGO and VIRGO detectors – at first to find the signal and then to identify its type.

"As a foundation for this, a major effort is needed in the next few years to compute the waveforms to be expected from various sources," Thorne says. He described recent progress toward this goal and outlined important, unresolved research questions at a symposium on future directions in general relativity research, held last month at the University of Maryland at College Park.

So far, researchers have concentrated mainly on the shapes of gravitational waves emanating from black-hole and neutron-star binaries. Along with the whirling descent of small black holes, neutron stars, and white dwarf stars into supermassive black holes, "these sources are expected to be the 'bread and butter' of the LIGO/VIRGO . . . diet," Thorne says. "Their waveforms should exhibit a wide variety of behaviors that carry a rich harvest of physical and astronomical information."

In the last three minutes before coalescence, spiraling binaries would generate gravitational waves that rapidly sweep upward in frequency from 10 hertz to 1,000 hertz, producing a distinctive "chirping" signal. Earth-based interferometers would observe several thousand cycles of this process.

New theoretical studies reveal that this chirping signal has a form so complicated that researchers could use it to infer the masses, spins, and orbital paths of the two bodies producing the gravitational radiation. From the inferred masses, scientists would have a good idea whether they were observing black holes or neutron stars.

In the final seconds before coalescence, the signal would change to reflect "tidal" distortions that the bodies induce in each other's shape just before they merge. In the case of two neutron stars, complete coalescence would occur within a few revolutions spanning less than a second, thereby shutting off the gravitational wave signal quite abruptly.

In principle, physicists could use the details of the coalescence waveforms to establish how a neutron star's mass depends on its radius. From this information, they could infer such characteristics as the density and composition of the nuclear matter making up these highly compact, massive stars. The possibility that stellar and black-hole coalescence also produces intense bursts of gamma rays adds to the interest in modeling the behavior of these binaries.

One intriguing possibility involves the use of gravitational wave signals from binaries in galaxies beyond the Milky Way as a cosmological probe. By determining the characteristics of a large number of binaries in which at least one partner is a neutron star, physicists could establish more firmly the relationship between distance and redshift – the increase in the characteristic wavelengths of light emitted by stars – caused by the expansion of the universe.

"By contrast with electromagnetic cosmological measurements, which suffer from light absorption and source evolution, this method will suffer just one type of propagation noise (gravitational lensing by mass inhomogeneities)," Cutler and his collaborators contend in their paper. Computer simulations show that signal distortions due to the bending of gravitational waves around large masses, such as distant galaxies, should be negligible compared with detector noise.

The central problem that theorists hope to solve before the gravitational wave observatories come on line concerns the behavior of a pair of orbiting, spinning black holes (SN: 9/3/88, p.152). "This is the Holy Grail of numerical relativity," Thorne says.

"Interacting astrophysical black holes are potentially the strongest source of gravitational radiation accessible to detectors like the LIGO/VIRGO ... system currently under construction," says Richard Matzner of the Center for Relativity at the University of Texas at Austin.

With the increasing availability of extremely fast computers with mammoth memories and with a better understanding of how to handle and interpret the complicated equations describing the gravitational interactions of a pair of black holes, this task now appears feasible, Matzner remarks.

Researchers are exploring several avenues toward solving the problem and eventually simulating in three dimensions the evolution of black-hole behavior, given any mass ratio and spin rate. So far, most efforts have concentrated on special cases involving two-dimensional black holes that aren't spinning (see box).

"We have a lot of work to do," Matzner says. "Maybe in five years we'll be able to predict the radiation emitted [by a black-hole binary]."

The race is on. Can the theorists calculate and predict what the waveforms will look like before the observers detect their first gravitational wave signals?

A variety of obstacles stand in the way of both the theoretical work and the construction of the detectors. Both projects are massive undertakings. Both face unforeseeable technical difficulties. And LIGO itself will cost about $250 million and must endure continued congressional scrutiny.

But if both endeavors succeed, a new field of astrophysics could open up around the study and interpretation of gravitational waves. □

## Ringing a black hole

Invisible, elusive, bizarre. These adjectives go naturally with the notion of a black hole.

Kip S. Thorne of Caltech has described this strange object in the following words: "Of all the conceptions of the human mind from unicorns to gargoyles to the hydrogen bomb, perhaps the most fantastic is the black hole: a hole in space with a definite edge over which anything can fall and nothing can escape; a hole with a gravitational field so strong that even light is caught and held in its grip; a hole that curves space and warps time."

The general theory of relativity has forced physicists to take black holes seriously. No one who accepts general relativity has found any way to overturn the prediction that black holes can form from the gravitational collapse of sufficiently massive objects and that they ought to exist in the universe.

But solving the relativity equations to predict precisely how black holes would behave and what types of gravitational waves they might generate has proved extremely difficult. Using supercomputers, researchers have so far managed to work out only a handful of special cases.

At the National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champaign, a team of researchers has now solved the Einstein equations to illustrate what happens in the brief interval just before a pair of two-dimensional black holes, rapidly spiraling in toward each other, finally merge.

At this stage, the two black holes generate such strongly varying gravitational fields that the situation is analogous to a huge gravitational wave sitting on top of a single black hole, says astrophysicist Larry L. Smarr, a member of the NCSA team.

This meant the researchers could study the complicated pattern of gravitational waves produced during the final stage in the coalescence of two black holes by looking at the interaction between a gravitational wave and a single black hole.

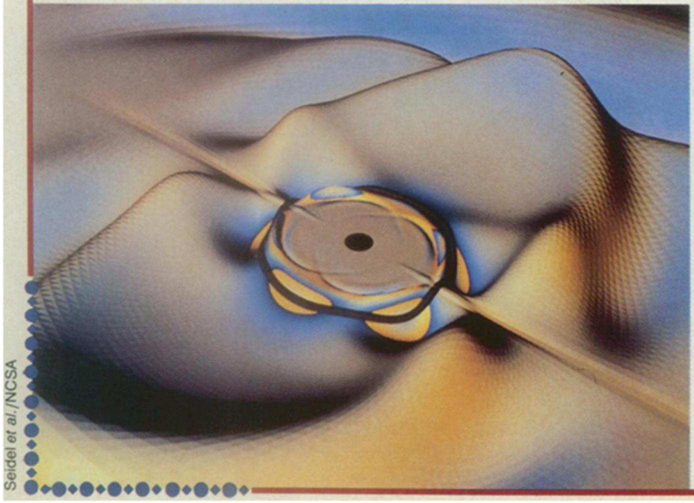
The results show that the wave's presence forces the black hole out of its stable, equilibrium state. Then, as the perturbing wave moves away, the black hole snaps back to its original state but overshoots it. The black hole ends up oscillating at a particular frequency. In other words, it rings like a bell. As it rings, the black hole itself absorbs and radiates gravitational waves.

Similarly, a pair of colliding black holes will quickly merge into a single black hole and begin oscillating with a characteristic frequency.

The NCSA researchers have now rewritten their computer program to handle three-dimensional black holes. "By 1996 or so, we should have enough [computer] power to run the full, three-dimensional version," Smarr says.

NCSA's Edward Seidel described the two-dimensional simulations at Physics Computing '93, a conference held earlier this month in Albuquerque.

*– I. Peterson*



Seidel et al./NCSA

*This frame from a videotape shows the result of an encounter between a black hole and a gravitational wave. The wave distorts the black hole, causing it to ring like a bell. This motion warps the spacetime around the black hole, creating new gravitational waves.*