Of Politics, Pulsars, Death Spirals—and LIGO

LIGO is an elegant little experiment that could make gravity-wave astronomy a reality—if only it weren't so expensive

In every respect save one, LIGO is quintessential Little Science.

The Laser Interferometer Gravitational Wave Observatory, as it is known in full, is a proposal to do exactly what its name suggests: search for gravity waves, the subtle undulations in space-time geometry caused by supernovas, colliding neutron stars, and other cosmic catastrophes. If built, and if it works as well as its designers hope, then LIGO could finally succeed in detecting these ghostly ripples after they have eluded more than two decades of experiments around the world. Just as important, it could transform the waves into a whole new window on the universe—perhaps even allowing the first direct observations of the Big Bang itself.

Despite its ambitious aims, however, LIGO is quite deliberately *not* being done in the classic Big Science style, with mega-collaborations and armies of anonymous postdocs. Quite the opposite. Most of LIGO's fundamental technology has been developed on the benchtops of Caltech and MIT by a handful of professors and graduate students. Its inherent difficulty has inspired those researchers to precisely the kind of creativity that is said to be the glory of small group science—a prime example being their development of a laser ranging device that can detect motions only one 100-millionth the width of a hydrogen atom. And LIGO's design is such that the researchers can continue in this small group style after the facility is built.

So LIGO has all the Little Science virtues—with just one eye-popping exception: its construction cost of $192 million would make it one of the most expensive single projects that the National Science Foundation (NSF) has ever undertaken. To condensed matter physicists and other NSF dependents who consider themselves the victims of a fiscal famine, LIGO looks like Big Science all the way.

"It's a most unfortunate situation that this field needs facilities of this size," sighs MIT physicist Rainer Weiss, a former molecular beam specialist who is now a co-investigator on LIGO. "Most of us in this field hate Big Science."

He has reason to feel defensive. Few of the perennial critics of Big Science have yet turned their guns on LIGO directly; after all, its cost is considerably less than the *uncertainty* in the $8-billion-plus price tag for the Department of Energy's supercollider. But the project has definitely gotten caught in the crossfire.

The House of Representatives has already used the need to protect small-scale science as an excuse to lop off NSF's request for new start money for LIGO in fiscal year 1991. (The lawmakers did not give the money to any other discipline, however.) And the Senate appropriations subcommittee on VA-HUD-Independent Agencies may well do the same when it takes up the NSF budget in mid-September. The result would be a delay of construction for at least another budget cycle—and no one knows how much longer.

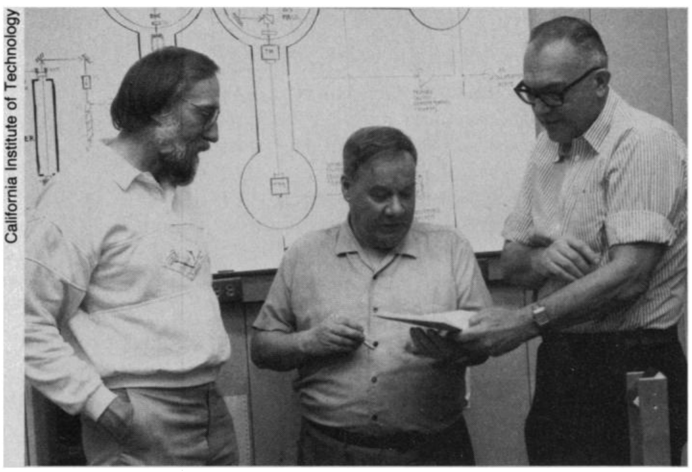
So why not just make a smaller, cheaper LIGO and avoid all this hassle? "Because unfortunately, nature is not so kind," says Caltech relativity theorist Kip Thorne, another of LIGO's co-investigators. LIGO has to be big to have a chance of detecting the gravity waves at all.

Very few physicists actually doubt the waves' existence, he says, largely because they are a fundamental prediction of the most widely accepted theory of gravitation, Einstein's general relativity. Einstein's basic idea was that every particle of matter in the universe causes a certain curvature in the fabric of space and time, in somewhat the same way that a bowling ball would make a depression in the middle of a trampoline. What we call "gravity" is simply a consequence of that curvature. (Put a marble on the trampoline and it will roll toward the bowling ball.) And gravity waves are just a rippling of the fabric caused by the motion or interaction of the particles of matter.

The problem, says Thorne, is that Einstein's theory also says that gravity waves are incredibly feeble. If a wave were to pass through the earth from, say, a supernova, the space-time ripple would set the planet to ringing like a bell. But the relative motion between any two atoms would be quite a lot smaller than the width of one of those atoms—less than one part in 10^{21}. You'd never notice it.

Indeed, says Thorne, no one had the slightest idea of how to measure such an effect until the 1960s, when University of Maryland physicist Joseph Weber started looking for the vibrations induced by gravity waves in massive bars of aluminum that had been carefully isolated from outside noise. Weber's work, along with the similar efforts he inspired around the world, ultimately yielded bar detectors capable of measuring gravity wave deflections to a few parts in 10^{18}. But even at that level of sensitivity, none of the bar detectors has ever found convincing evidence of a gravity wave from any source. (It should be said that Weber has spent the past two decades claiming that he *has* seen such evidence. But very few other physicists agree with him.)

In any case, in the late 1960s several physicists independently realized that they might be able to do better with a laser-based detector. Among them was Weiss, who at that time found himself teaching the MIT course in general relativity while struggling to stay just a few days ahead of his students.



California Institute of Technology

LIGO ringleaders. *Director Vogt (right) confers with co-investigators Thorne (left) and Drever.*

"When we got to the section on gravity waves, I couldn't figure out what was going on at all," Weiss recalls. "So I had to figure out a method to understand the theory in terms of an experiment." What he came up with was a homework problem: the students were supposed to imagine two masses suspended in space a fixed distance apart, and then calculate how the measured distance between the masses would change as a passing gravity wave set them ever so slightly moving in and out, in and out. "And then lo and behold, it clicked," he says: "You could actually do this with light!"

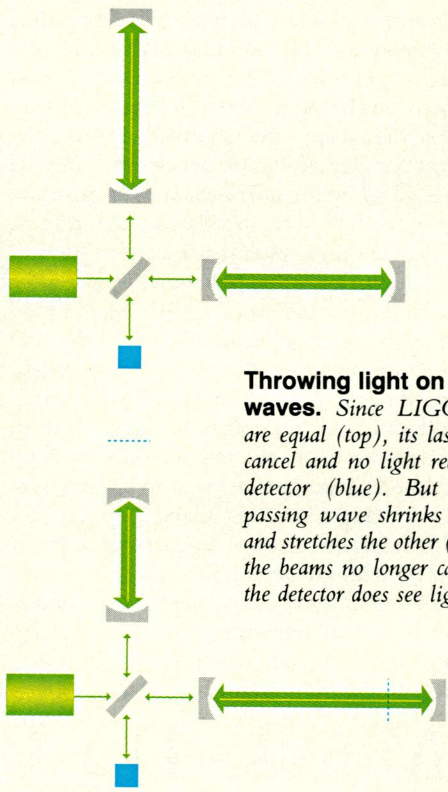
The key, he realized, was to monitor the distance between the two masses using a long-established optical technique known as interferometry. First, a laser would replace one of the masses and direct a steady beam of light at the other mass. Next, the second mass would be fitted with a mirror, which would reflect the laser beam straight back where it came from. And finally, an optical system next to the laser would take the returning light waves and combine them with a portion of the original laser light. The result, says Weiss, would be "interference fringes"—a pattern of light and dark bands that could be monitored by a detector. Moreover, these fringes would be extremely sensitive: even a tiny shift in the position of the second mass would in principle cause a noticeable change in the fringe pattern.

The measurement still wouldn't be easy, Weiss knew, but 6 months of calculations convinced him that a gravity wave detector based on laser interferometry just might work. Nor was he alone in that conviction: even as Weiss was setting up his own small-scale experiments, other groups were pursuing the approach independently. Weber and his students made the first experimental tests of a laser detector in 1972. A group in Munich started work in 1975, and another in Glasgow in 1977. And then in the late 1970s, at the instigation of Thorne, Caltech set up a well-funded experimental group of its own and hired Ronald Drever from the Glasgow group to head it.

By 1983, Weiss' group at MIT had merged with the Caltech team to form what is now the LIGO partnership—largely because the NSF, which was providing development money, declared that it was not about to support two groups simultaneously. Then in 1986, in response to NSF's insistence that the growing project needed better coordination, the LIGO team brought in cosmic ray physicist Rochus E. Vogt as director and principal investigator. "And I had been planning an easier life," laughs Vogt, who had just stepped down as Caltech's provost. The four co-investigators are now Weiss, Thorne, Drever, and Caltech's Frederick Raab.

In its current incarnation, says Vogt, the LIGO proposal actually calls for two facilities separated by several thousand kilometers. Only by recording the same signal in at least two different detectors simultaneously can you be sure you are not just seeing some random seismic noise. Three or four detectors would be even better, says Vogt. And, as it happens, two more laser interferometers are indeed being planned for the late 1990s in Europe, one by a British-German collaboration, and the other by a French-Italian group. Together the four detectors will also allow researchers to pinpoint the gravity wave sources on the sky to a resolution of about 1 arc minute; with only two detectors, says Vogt, you can only say that the source lies somewhere along a circle in the sky.

In any case, he says, each U.S. LIGO facility will consist of a pair of 1.3-meter-wide vacuum tubes, joined in the shape of a huge "L." Each tube would be 4 kilometers long and would have a target mass hanging from a quartz fiber at the far end. The laser system will sit at the corner of the L, where its beam will be optically split in two and sent down the vacuum tubes to both masses simultaneously. The idea is that a passing gravity wave will cause one mass to swing inward while the other swings outward, and vice versa; comparing these two motions will provide a crucial cross-check on the detection.



Throwing light on gravity waves. *Since LIGO's arms are equal (top), its laser beams cancel and no light reaches the detector (blue). But when a passing wave shrinks one arm and stretches the other (bottom), the beams no longer cancel and the detector does see light.*

The overall size of LIGO is a compromise between economics and the need for detector sensitivity, says Vogt. Stainless steel vacuum pipes, transportation, welding, testing—all that is expensive, he says, so expensive that this "low-tech" component of the project actually accounts for 80 to 90% of the cost. However, if and when a gravity wave passes, the relative displacement between the laser and the target masses will be proportional to their distance apart. So the longer LIGO's arms are, the easier it will be to measure a given gravity wave's effects. A prototype laser detector with 40-meter arms has been operating for several years now at Caltech; the full-scale LIGO, with it 4-kilometer arms, should gain a factor of 100 in sensitivity simply because of its size.

Another major boost in sensitivity comes from the fact that LIGO's laser beams will actually make the 8-kilometer round trip down each arm hundreds or thousands of times, bouncing back and forth between mirrors that can sustain at least 10,000 such bounces before they lose enough photons to dim the laser beams significantly. In effect, this trick makes the arms seem hundreds or thousands of times longer than they really are, and increases the sensitivity accordingly.

The Caltech prototype has already measured movements of 10^{-14} centimeters in its target masses, Vogt says, and the LIGO researchers are confident that their full-size laser system will ultimately be able to measure movements of some 10^{-16} centimeters. That is about one 100-millionth the width of a hydrogen atom, and should be sufficient to let the full-scale LIGO detect gravity waves as weak as a few parts in 10^{23}. And that, in turn, should allow LIGO to pick up waves from a wide variety of astrophysical sources.

As impressive as that performance would be, however, a skeptic still has a right to ask, "So what?" After all, $192 million is a pretty stiff price for simply verifying a prediction of general relativity—especially when most physicists believe in the theory anyway. "The thing about gravity is that it's boring, because you understand it completely," says Princeton's Phillip Anderson, a Nobel laureate for his theoretical work on condensed matter and a frequent critic of Big Science. "If it didn't have Einstein's name on it, would you give a damn?"

The LIGO team's answer is that such criticisms miss the point. They aren't proposing LIGO just to verify the existence of gravity waves, they say, although they certainly hope it will do that. What they're after is a whole new branch of astrophysics.

"Gravity waves come from places where the gravitational field is immensely strong, or where the system is highly dynamical," says Caltech's Thorne. "We're talking about the collapsing cores of supernovas, or the collisions of black holes and neutron stars—events you have no hope of seeing with light."

A prime example of such an event would be the death spiral of a binary pulsar, says Thorne. Our own galaxy is already known to contain at least one binary pulsar: discovered in 1974 by Princeton's Joseph Taylor, it consists of two 10-kilometer balls of dense nuclear matter—neutron stars—whirling around each other in a close circular orbit. This system is almost certainly a powerful emitter of very low frequency gravity waves, says Thorne. No one has detected the radiation directly, of course. But the neutron stars are clearly losing orbital energy, drawing gradually closer together. And after 16 years of monitoring, Taylor still finds that the rate at which they lose energy is precisely the rate at which Einstein's theory says they should—assuming that all the energy is going into gravitational radiation.

"If you follow this system for a few hundred million years," says Thorne, "the neutron stars would eventually spiral together and merge in a violent, dynamical way." Conceivably, he says, they could even coalesce into a black hole. In any case, during the last few minutes of this death spiral the frequency of the gravitational radiation would get high enough for LIGO to detect it above the background seismic noise.

Now obviously, says Thorne, 100 million years is too long to wait for a signal. But binary pulsars are thought to be reasonably common objects on a cosmic scale. So if LIGO achieves the sensitivity that he and his colleagues hope, says Thorne, then its range would encompass so many galaxies that it would see several such death spirals per year.

Each time this happened, he says, the target masses at the end of LIGO's arms would first begin to undergo a sinusoidal motion, which would rapidly increase in amplitude and frequency as the neutron stars drew inward. Then, at the instant of the merger itself, the masses would be tossed about by a violent outburst that nobody knows how to calculate. And finally, in the aftermath, they would undergo a fading sinusoid as everything on the newly merged pulsar or black hole settled down. The resulting signal profile would be a treasure trove for the theorists, says Thorne. It would tell them a great deal about the structure and behavior of nuclear matter in extremis. And it would likewise tell them about the behavior of gravity when space and time are being very drastically curved—a much more stringent test of Einstein's theory than of gravity waves themselves.

Meanwhile, says Thorne, LIGO should also be seeing other sources. Supernovas, for example: if these cataclysmic explosions generate gravity waves as strongly some theorists think, then LIGO could detect about a dozen of them per year. Or ultramassive black holes: these enormous, billion-solar-mass objects seem to lie at the core of every quasar, generating the quasar's fierce luminosity by gulping down huge quantities of stars and gas. Even many normal galaxies (including ours) are thought to harbor million-solar-mass black holes. Whatever collisions and mergers produced these behemoths, says Thorne, some of them likely produced such strong gravity waves that LIGO could see them anywhere in the observable universe. These events could come as frequently as once per year.

And then there's Weiss' personal favorite: the Big Bang. According to some scenarios for what happened in the very early universe, he explains, there should be residual gravitational radiation that LIGO could detect. If so, it would provide clues as to what went on during the first 10^{-43} seconds after the Big Bang—the so-called Planck era, which many physicists believe can only be described by the unknown laws of quantum gravity. "It's very speculative," he admits, "but *that's* the experiment I want to get to."

Speculative or otherwise, the potential scientific payoffs from LIGO were sound enough to win it strong support within the NSF hierarchy, up to and including outgoing director Eric Bloch. The LIGO group submitted its conceptual design to NSF in December 1989. The foundation accordingly listed LIGO as a new start in its fiscal year 1991 budget request, asking Congress for $47 million as a down payment on a 4-year construction program.

And Congress, acting predictably enough in an era of high-anxiety deficits, balked. The question was not one of science so much as priorities: How can we justify giving so much money to one experiment?

Vogt, who has spent quite a bit of time lately arguing LIGO's case on Capitol Hill, replies that that is a question only the political system itself can answer. "It's not up to me to decide what the country's priorities are," he says. "It's only up to me to offer the country beautiful choices."

That said, however, he takes strong exception to calling LIGO "one experiment." "That's like calling the Palomar telescope a single experiment," he says. "I'm building an astrophysical observatory, and it's going to operate in an observatory mode for 50 years." In particular, LIGO has been designed with room in the vacuum tubes for multiple laser beams, so that several groups of experimenters can be testing out new optical systems and new detector technology at the same time that others are taking data.

"The facility may be Big Science," agrees Weiss, "but I envision the work itself to still be in the style of small science, with four to six people in a group."

It remains to be seen whether such arguments will carry the day. If the Senate okays the money this autumn, the House may be persuaded to go along in conference committee, in which case LIGO could start construction almost immediately. If not, then the project will be delayed for at least another budget cycle while the LIGO team waits and waits, refining their technology even further on the lab bench.

■ M. MITCHELL WALDROP

Merck–Du Pont Venture: Prescription for Success?

Two corporate giants recently formed a joint venture that may set trends for years to come in the world of pharmaceutical research

AFTER WALL STREET CLOSED for trading on 25 July, the nation's leading drug company sent out a press release containing a bombshell. Merck & Company, the announcement said, was teaming up with chemical giant Du Pont to form a joint venture: a new pharmaceutical firm. Although the $51-billion American drug industry has gotten used to mergers and liaisons, this was a surprise—both because of the size and success of the companies involved and the innovative nature of the venture, which leaves the parent companies' operations separate.

The next morning pharmaceuticals analysts mumbled over their copies of the *Wall Street Journal* as they puzzled out the deal, which observers say could become a trendsetter. The analysts understood the tough economic environment that prompted the venture. But they wondered what was in it for the partners—particularly Merck, which has been far more successful in pharmaceuticals than Du Pont has.

The stated reason for the joint venture was that the companies are pooling their resources to offset the high cost of bringing a drug from the lab bench to the pharmacy shelf. That process takes a decade and $230 million on average—and that cost is being