self, including a study of how frog embryos develop in weightless conditions and the way the human inner ear responds to gravity-free conditions.

Now, as France's research minister, she has the chance to shape the nation's entire science effort. So far, she has not launched any specific initiatives, most of which will have to wait until the proposed budget is approved by the Council of Ministers in September. But in a number of speeches and policy statements, she has set down her main priorities, including stemming France's "brain drain" by making research careers in France more attractive. "We must liberate the creativity of researchers," she says, for example, by making it easier for them to go into industry or teaching while still retaining positions with basic research agencies such as CNRS. Haigneré also wants to ensure that France takes its rightful place in the European Research Area (*Science*, 29 June 2001, p. 2425). And although she says that fundamental research should always be at center stage in France's science effort, she wants to do much more to boost technological innovation.

Over the past few weeks, Haigneré has been forced to fight a rearguard action against proposed cuts of 7.6% in the $9 billion France spends on nonmilitary R&D each year. The proposal, first reported by the daily newspaper *Libération*, which had obtained an internal government working document, came as a major shock to French scientists. Just last month, they heard President Chirac repeat—in a speech at the Airbus factory in Toulouse—his campaign promise to boost French R&D spending from its current 2.17% of gross domestic product to 3% by 2010.

Although Haigneré and finance ministry officials decline to confirm specific figures, she says she "battled a great deal to get the message across" to Raffarin that such a cut was unacceptable. "The message was understood," Haigneré says. "Things are not as good as I had wished but much better than [they were]." She sees one positive result from the controversy over science budget cuts: "Now everyone is talking about research, which they weren't before!"

If the current government serves out its full term, Haigneré could expect to be research minister for the next 5 years. Since her appointment, she says she has had little time to keep up with her normally rigorous daily exercise schedule. "Being a minister takes a lot of energy, but after a period of adjustment I hope to find a rhythm so that I can stay in [physical] shape." And she has not given up the idea of returning to space one day: "I will never close that door."

—MICHAEL BALTER

ASTROPHYSICS

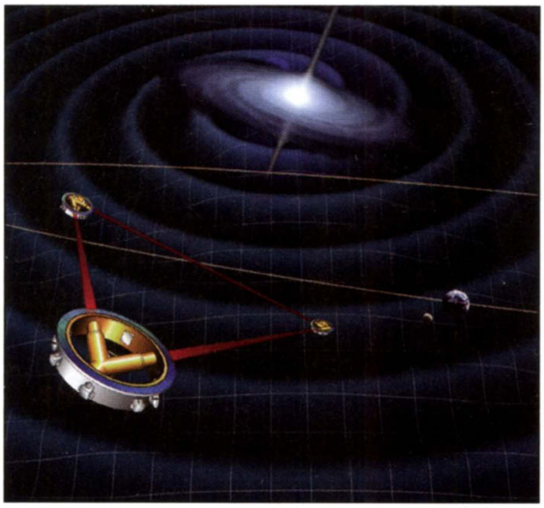
Gravitational Wave Hunters Take Aim at the Sky

European and American scientists are eager to build LISA, a 5-million-kilometer triangle of spacecraft tuned to murmurs from the biggest black hole encounters of all

UNIVERSITY PARK, PENNSYLVANIA—The idea sounds outlandish. Launch three spacecraft into orbit around the sun and spread them into a triangle 5 million kilometers on a side. Use 1-watt lasers and 30-centimeter telescopes to monitor changes in the relative distances of metal cubes that float quietly within each vessel. Gauge variations as small as 10 picometers—yes, just one-tenth of an angstrom. "Invariably, these numbers induce giggles or outright chuckles in the back of the room," says optical engineer Eugene Waluschka of NASA's Goddard Space Flight Center in Greenbelt, Maryland.

However, the next steps are spurring Waluschka and his colleagues past the snickers: Convert the data into details about passing gravitational ripples in the fabric of spacetime, yielding exquisite insights about merging black holes that astronomers can get in no other way. That's the promise of the Laser Interferometer Space Antenna (LISA), a project that has graduated from years of blue-sky dreams to a joint European-U.S. mission gaining momentum toward a planned launch in 2011.

LISA will not supersede the Laser Interferometer Gravitational-Wave Observatory (LIGO) and similar devices on the ground, which are striving to suppress the noises of Earth (see sidebar, p. 1115). Instead, LISA will observe a different part of the gravity spectrum, much as a radio telescope sees aspects of the universe that an optical telescope cannot. Whereas LIGO and its brethren try to detect high-frequency bursts from sudden events, such as off-center supernova blasts or the collisions of two neutron stars or black holes with starlike masses, LISA will tune into deep gravitational murmurs that rumble for months or years. If LIGO listens for the squeaks of cosmic mice, LISA will record intricate whale songs.



Small surf. Passing gravitational waves would distort the vast LISA triangle by hundreths of a nanometer.

CREDIT: NASA/JPL

The vocalists, according to theory, include binary pairs of white dwarfs in our Milky Way so numerous that they generate a persistent gravitational buzz, like the static between AM radio stations. More compelling are small black holes swooping into big ones and the mergers of supermassive black holes at the cores of galaxies—the most energetic events the universe can spawn. "That's the gold-plated objective for LISA," says U.S. project scientist Robin Stebbins of NASA Goddard. "Ten years ago, people didn't even think there were massive black holes in most galaxies. The science of LISA keeps getting better."

That consensus echoed through a recent meeting* of more than 100 researchers here at Pennsylvania State University. Daunting tasks loom, especially getting a firmer commitment from the U.S. government to fund its share of the project. The total cost may rise from today's estimate of $600 million to more than $1 billion by launch. However, design and engineering are under way for a European Space Agency (ESA) satellite flight in 2006 to validate crucial LISA technology in the microgravity of space. "People are ready to cut metal," says astrophysicist L. Samuel Finn of Penn State, the meeting organizer. "It's no longer an academic exercise."

* 4th International LISA Symposium, 19–24 July.

A distant whisper

Plans call for LISA's trio of identical spacecraft to orbit the sun at the same distance as Earth, trailing 50 million kilometers behind our planet. Seen from above the solar system, the center of the LISA triangle will track Earth's orbital path, while the three vessels pinwheel around that center once a year (see figure below). Each spacecraft will look like a metallic doughnut enclosing a Y-shaped assembly of instruments.

More critical than the vessels are their cargo: six gold-platinum cubes just 4.6 centimeters on a side, with one floating freely inside each upper arm of the Y. These are LISA's "proof masses," the bodies drifting peacefully through the warp and woof of spacetime. For LISA to work, each 2-kilogram cube must trace an independent orbit around the sun. The spacecraft will isolate them within vacuum chambers and provide the necessary hardware—lasers and small telescopes—to monitor fluctuations in their relative motions.

As the orbiters travel through space, each will track changes in its motion relative to the other two, rather than the far harder task of measuring absolute distances. The aim is to detect cyclical expansions and compressions of spacetime created by one massive body spiraling close to another, like waves from an eggbeater whirling in batter. Each spacecraft's optical system will combine the laser beams to create a fast-changing interference pattern, with about a million dark fringes riffling past each second. Spacetime waves will alternately enhance and retard that pattern with signatures that range from subtle to dramatic.

Indeed, the expected strength of gravitational radiation at LISA's low frequencies—cycles lasting tens to thousands of seconds—is the main reason why astronomers are enthusiastic about LISA. "With LIGO [in its first generation], you're really at the margins of detectability, struggling to try to dig signals out of the noise," says astrophysicist Neil Cornish of Montana State University, Bozeman. "People assume that's true for gravitational waves in general, but it is not at all the case for LISA. We have massive signal-to-noise, far better than for some optical instruments. We will see sources within the first hour of turning on."

Still, the demands for utterly quiet spacecraft surrounding the proof masses are steep. "It's a new concept in serenity," says physicist Bonny Schumaker of NASA's Jet Propulsion Laboratory in Pasadena, California. "She's a very sensitive girl, this LISA. She demands the most pristine environment imaginable." Schumaker calculates that a nudge equivalent to the air pressure from a human whisper 40 kilometers away would tip a cube out of whack.

Today's technology suffices to cancel such disturbances, says Karsten Danzmann, director of the Albert Einstein Institute in Hannover, Germany, and ESA's mission scientist for LISA. "There are no breakthroughs required, no miracles," he says. "Just sound engineering practices will be enough to bring it to the sensitivity we envision." For example, new microthrusters will keep the spacecraft centered around the masses by spitting vanishingly thin jets of ions into space.

To get within a factor of 10 of LISA's requirements, ESA and NASA physicists will fly two test packages of proof masses and hardware inside the same ESA satellite, called SMART-2, in 2006. "The only thing we cannot simulate on the ground is zero gravity," says physicist Stefano Vitale of the University of Trento, Italy, architect for the ESA package on the test flight. His colleagues repeatedly teased him about one other tough issue that LISA will face: a distinct lack of graduate students in space to fix the instruments if something goes wrong.

Bothrodesy: It's the pits

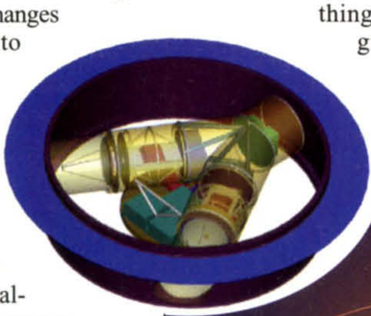
Beyond some sure-fire sources, astrophysicists differ about LISA's most promising quarries. Calculations suggest that LISA will easily see emissions from several thousand close pairs of white dwarfs in our galaxy. These partners shed gravitational energy as they whirl more tightly, often speeding around each other in mere minutes (*Science*, 15 March, p. 1997). Waves from another 100 million such binaries in the Milky Way will blur into an underlying "confusion" noise. A few binaries involving neutron stars or stellar-mass black holes also should trigger LISA, although their numbers are poorly known.

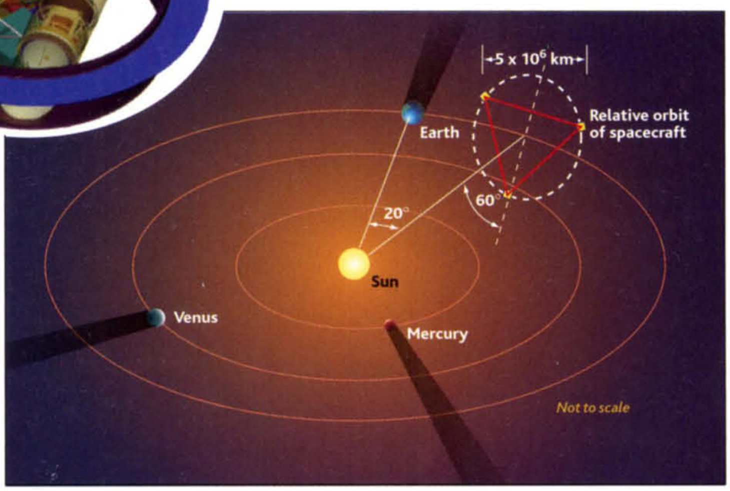
Far more tantalizing is the prospect of precisely measuring the fantastic gravitational fields near black holes, a venture dubbed bothrodesy by astrophysicist E. Sterl Phinney of the California Institute of Technology in Pasadena. (In ancient Greece, a *bothros* was a sacrificial pit or well.) Phinney thinks LISA will provide the best test of Einstein's general theory of relativity by monitoring the plunges of pedestrian black holes—with 5 to 10 times the mass of our sun—into gigantic ones at the hearts of galaxies.

"The smaller hole will spend its last 10,000 to 100,000 orbits in a strongly relativistic regime," Phinney says. "There will be hundreds of these at the same time, producing the richest and most complicated signals that LISA will see." Unraveling the end stages of those signals, which theorists cannot begin to forecast today, may be "long, messy, and painful," Phinney says—but that's the sort of pain astrophysicists crave.

Another potential signal that defies prediction is the merger of two supermassive black holes. That event, anywhere in the universe, would warp spacetime between LISA's proof masses more severely than anything else. However, it's not clear whether LISA will be lucky enough to catch one during its operational lifetime of 3 to 10 years. A recent analysis of active radio galaxies concluded that such mergers could happen about once a year (*Science*, 2 August, p. 753). That's more optimistic than other studies, which suggest that pairs of giant black holes could get trapped in orbits a few light-years wide for billions of years.

"We know galaxies are merging today," says astronomer Douglas Richstone of the University of Michigan, Ann Arbor. "The rate has declined, but they continue. So at any given time there should be binary supermassive black holes in the pipeline. One of them somewhere will be just about to go down the chute." Still, the uncertainties in event rates prompt this warning from physicist Peter Bender of JILA in Boulder, Colo-





Rear wheel. LISA probes (*inset*) would circle a "hub" 50 million km behind Earth.

LIGO: The Shakedown Continues

Thirty-three months after its dedication, the $365 million Laser Interferometer Gravitational-Wave Observatory (LIGO) will begin its first "science run" 23 August. For 17 days, physicists intend to keep their beams of light on target at LIGO's sites in Louisiana and Washington state (*Science*, 21 April 2000, p. 420) for simultaneous data collection. "If we can keep running, we'll reach interesting scientific limits," says deputy director Gary Sanders of the California Institute of Technology (Caltech) in Pasadena. Don't expect startling news, however: According to the latest estimates, LIGO's detectors are still 100 to 1000 times more jittery than their blueprints demand. Only a nearby supernova might rise above the background noise.

Not to worry, Sanders says: "It's what we expected during commissioning. We've made steady progress in reducing the noise since we turned on." Adds Caltech colleague Ron Drever, a pioneer of the laser interferometry technique: "I think people are jolly well pleased."

Many of LIGO's systems have surpassed expectations. The immense vacuum chambers, spanning 8 kilometers of steel tubing at each site, hold tight with nary a leak. The lasers are stable, snapping back to their "locked" focus through the optics after each engineering adjustment.

Still, figurative and literal bumps have jostled the team. The worst problems are local traffic and commercial logging in the woods around the Louisiana site. Damp soil channels the vibrations of a felled and dragged log at just the right frequency—about 2 hertz—to jiggle LIGO's nested sets of springs. "When a tree falls and there's nobody there, we hear it," says physicist David Shoemaker of the Massachusetts Institute of Technology in Cambridge. So for now, most usable data come only at night.

To compensate, the team has accelerated testing of a new system that will sense and actively suppress vibrations. Plans call for engineers to install that fix after a second science run in December and early January has ended. By mid-2003, "we expect that we will be within a stone's throw of the target sensitivity for our first-generation detector," Shoemaker says.

That timeline forces a tough decision. LIGO's leaders must apply to the National Science Foundation for "Advanced LIGO," a $100 million upgrade for a stronger laser, better optics, quieter suspension, and more sophisticated protection from vibrations. A successful proposal this year would keep the project on track for an upgrade starting in 2006. In the minds of most observers, that's the only realistic chance for LIGO to see gravitational waves, as Advanced LIGO would search a volume of space 10,000 times larger than LIGO 1. However, the team is mulling whether to wait a year, pending progress in the first science run. "We're in this dilemma where we may propose the construction of an upgrade before we have really shown that we've fulfilled the promise of the first round of detectors," says Sanders.

Earth tones. Local noise from traffic and logging still jitters the sensitive optics in LIGO's 4-km arms.

LIGO hasn't yet won the hearts of astronomers, but fewer disparage the project now than early in its history. "I think astronomers are ignoring LIGO," says Douglas Richstone of the University of Michigan, Ann Arbor. "They just don't think it will get sources. But if it does," he adds with a smile, "it will inspire a great deal of interest." –R.I.

rado: "We can't guarantee any of the massive black hole science."

Even without that prize, LISA still may expose how the cores of galaxies grow. Thanks to the expanding universe, higher-pitched gravitational signals from more frequent mergers of distant, smaller black holes will stretch into LISA's low-frequency waveband. "There's a good chance that supermassive black holes build up from the mergers of black holes with a few hundred to a few thousand solar masses," says Bender. "LISA could do a lot to unravel that process."

Finally, some sources might not fit any category. Montana State's Cornish says that searching for novel waves in the data will be similar to code-breaking: finding signs of a pattern with little or no knowledge of its template. "With luck and ingenuity, we may be able to figure out what those unexpected sources are," Cornish says. "But it's going to be phenomenally hard."

CREDIT: LIGO LIVINGSTON LABORATORY

Transatlantic glow

The challenges and promise of LISA have forged tight bonds on both sides of the pond. If the camaraderie at Penn State was any indication, LISA will become a model space mission for international collaboration.

LISA is a cornerstone mission for ESA, which has committed to proceeding with the full project. NASA has not yet done so, although its share of the 2006 test flight appears solid. LISA program scientist Michael Salamon of NASA Headquarters in Washington, D.C., told the audience that LISA is one of the two highest priority missions for the next 2 decades in a soon-to-be-released road map for the agency's Structure and Evolution of the Universe theme. The other, called Constellation-X, is a fleet of advanced x-ray telescopes that would work in unison.

Many scientists, however, worry that future NASA budgets may belie Salamon's reassuring words. "As things stand now, if you look at the numbers, NASA can't do LISA and Constellation-X simultaneously," observes Penn State's Finn. "ESA is much further along in its commitment to LISA, and that has already caused some problems. If NASA doesn't get caught up, those problems will get worse."

ESA representatives are happy with NASA's apparent wish for a true 50–50 partnership on LISA, but they concur with Finn's assessment. "It would be extremely negative if a lack of funds [from NASA] were to induce a delay or cancellation," says Alberto Gianolio, LISA study manager at ESA in Noordwijk, the Netherlands. "That would be a major blow to our cooperation."

But as fireflies glowed rhythmically in the heavy calm of Pennsylvania summer evenings, few scientists wanted to dwell on such pitfalls. "I've been retraining myself as a gravitational wave astronomer," said Cornish. "We're virtual astronomers at the moment, but it becomes more realistic with each passing month."

–ROBERT IRION