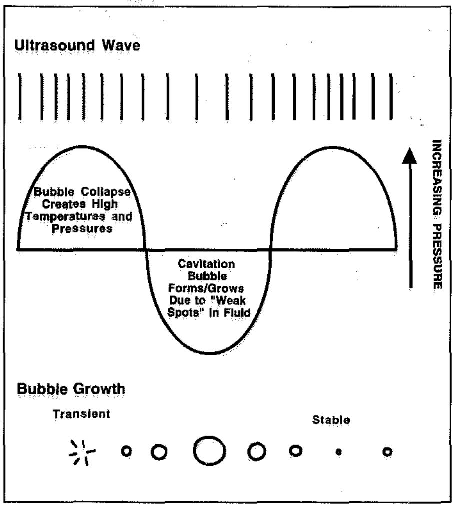


As an ultrasound wave propagates (top), it generates regions of alternating high and low pressure (middle). A bubble (bottom) can form in a low-pressure zone, and will expand and contract with successive pulses until it grows too big to support itself and implodes, creating tremendous heat and pressure within.

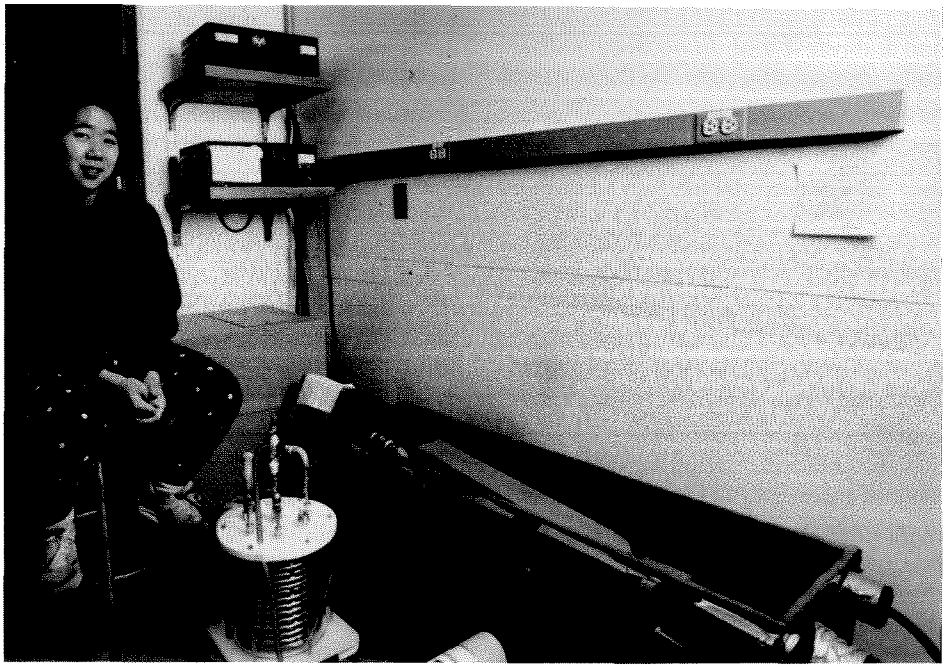
But Only Dogs Can Hear It

In 1927, Alfred Loomis noticed that ultrasound did strange things to dissolved chemicals, but ultrasound was hard to make and nobody got very excited about his discovery. There matters stood until the early 1980s, when cheap and reliable ultrasound generators became available.

In *The Hunt for Red October*, a Soviet nuclear-missile submarine is outfitted with a revolutionary propulsion system that virtually eliminates cavitation noise. In the words of the novel's Oliver Wendell Tyler, ex-submariner turned U.S. Naval Academy teacher, "When you have a propeller turning in the water at high speed, you develop an area of low pressure behind the trailing edge of the blade. This can cause water to vaporize. That creates a bunch of little bubbles. They can't last long under the water pressure, and when they collapse the water rushes forward to pound against the blades. That . . . makes noise, and us sub drivers hate noise." *Red October* would have made it to North America undetected, had it not been for the U.S.S. *Dallas*'s Sonarman Second Class Ronald "Jonesy" Jones, "one of the ten best sonar operators in the fleet," who "had been asked to leave the California Institute of Technology in the middle of his junior year. He had pulled one of the ingenious pranks for which Cal Tech [sic] students were justly famous." But a short in a bad switch started an electrical fire that "burned out a lab, destroying three months of data and fifteen thousand dollars of equipment." So Jonesy joined the Navy, where he was saving up to finance his return.

More broadly, cavitation is the formation of vapor bubbles in any liquid, even molten metal, caused by a pocket of reduced pressure within the liquid. "Cavitation is the death knell of subs," agrees Professor of Environmental Chemistry Michael Hoffmann, who never taught the fictional Jonesy. In Hoffmann's laboratory, cavitation also means curtains for pollutants lurking in water, but it's salvos of ultrasound, not depth charges, that deliver the lethal blow. There is a resemblance between the two methods, however—both rely on pressure waves for their effectiveness. The United States alone generates more than 540 million metric tons of hazardous solid and liquid industrial waste annually, according to Hoffmann, who estimates that some 10 percent of the liquid portion might be treatable with ultrasound. That 10 percent would fill a 21-mile-long train of tank cars daily.

Sounds become inaudible to humans somewhere above 15 kilohertz (kHz), or 15 thousand cycles per second. The threshold decreases with age—few sixty-somethings can hear tones higher than



Hua sits next to the flow-through reactor. The reactor itself is invisible within the coffinlike soundproofing, but the top of one of the ultrasound generators can be seen. The water recirculates through a cooling coil at her feet. The boxes on the shelves behind her are the ultrasound generators' power supplies.

8 kHz. (A piano's eight octaves run from 16 Hz to 4,186 Hz.) Above audible sound lies ultrasound, ranging from 16 kHz to several million hertz. In 1927, Alfred Loomis noticed that ultrasound did strange things to dissolved chemicals, but ultrasound was hard to make and nobody got very excited about his discovery. There matters stood until the early 1980s, when cheap and reliable ultrasound generators became available. Kenneth Suslick (BS '74), now at the University of Illinois, began experimenting with ultrasound as an initiator of chemical reactions, and others, particularly in Germany, followed his lead. A German grad student, Claudius Kormann (PhD '89), got Hoffmann interested in using ultrasound-driven reactions to destroy waterborne pollutants.

Sound waves are pressure waves. They travel through a medium by alternately squeezing and stretching it. As the molecules move apart from one another, the local pressure drops, and—presto!—cavitation occurs. Any gases or volatile liquids dissolved in the water contribute their vapors to the bubble as well. Once a bubble forms, it grows and shrinks with each successive wave. Each time it grows, its expanded surface area and lowered internal pressure allow more vapor to diffuse into it. The influx of new molecules prevents the bubble from collapsing quite as far during the compression that follows, and allows it to grow even bigger on its next expansion. In less than 100 billionths of a second, the bubble reaches a size whose natural resonance frequency is the ultrasound's frequency—for example, 20 kHz equals a bubble roughly 150 microns in diameter. The bubble absorbs the ultrasonic energy like mad, swells like an exploding depth charge, and collapses.

In the crush that follows, the bubble's gas molecules slam together at pressures hundreds of times that of sea level, as measured by the shock waves they produce. Intense pressure generates intense heat. Suslick and others have measured evanescent vapor temperatures of 5,500° C during those last few nanoseconds, while the bubble's liquid skin can reach 2,100 degrees. (An acetylene torch burns at around 2,400° C.) But because the bubbles are so small, the bulk liquid heats up only very slowly.

Fifty-five hundred degrees is just a wee bit cooler than the sun's surface, and it's plenty hot to destroy any organic chemical you care to name. You can get direct pyrolysis—combustion in the form of microscopic underwater flames that cause the liquid to glow the color of a gas-stove burner. Furthermore, the heat dissociates water molecules, and the OH radicals thus formed are powerful oxidants. Such radicals are dangerous terrorists in the wrong places, because

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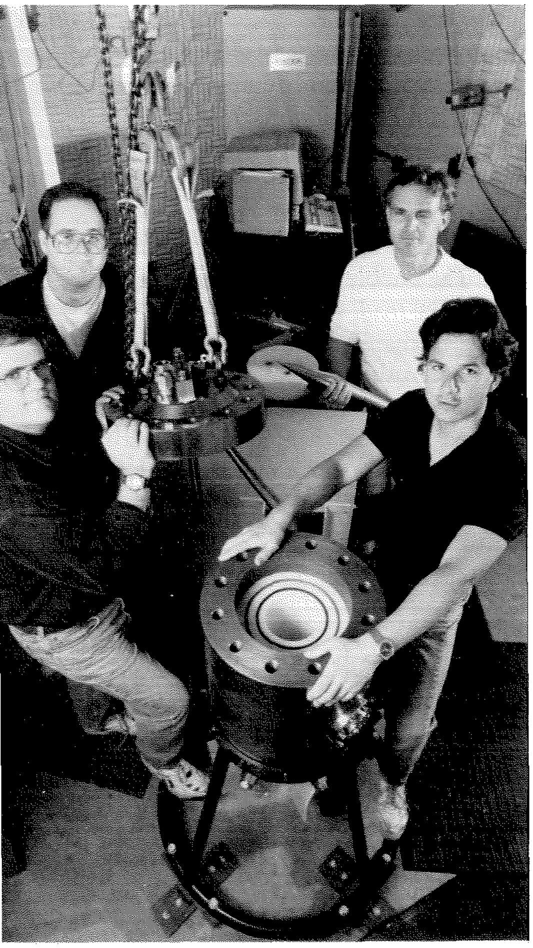


From left: Willberg, Lang, Kratel, and Hoechemar gather around the pulsed-power reactor. Willberg is steadying the reactor's lid, which weighs several hundred pounds all by itself. The nine-inch spike on the lid's underside is one electrode. Kratel holds the other, which is the general size and shape of a mortar round. The countertop behind them hides the capacitor bank. Note the soundproofing on the walls.

they pounce upon the first molecule they find and tear it limb from limb. If these molecular assassins don't find a soft target within the bubble, they diffuse out into the liquid to do their wet work.

Something else happens in ultrasound-irradiated water. At temperatures of more than 374° C and pressures in excess of 221 atmospheres, water goes supercritical—its vapor and liquid phases become indistinguishable from each other. This is a whole new substance, with properties completely unlike the garden-hose stuff. The density drops by a factor of five, and the viscosity by a factor of almost 1,000. Consequently, things diffuse much faster. And the pK_a drops to six, giving water the acid strength of soda pop. (Ever leave a nail sitting in a jar of Coke?) These changes greatly accelerate chemical reactions.

These processes continue as long as the ultrasound is left on, until there's nothing left of the pollutants but simple substances like nitrate, sulfate, carbon dioxide, and water. How much of something gets destroyed by which method depends on the pollutant's initial concentration—the more concentrated, the more pyrolysis.

With such made-to-order mayhem available, ultrasound could be a really good way to get rid of some really nasty stuff. But so far, Hoffmann's group is the only one exploring the chemistry of ultrasound reactions as they apply to pollutants. Says Hoffmann, "We are doing small-scale experiments, trying to understand how the processes work and how to optimize them." The group uses several experimental setups of varying sizes and designs.

In one early effort, Anastassia Kotronarou (PhD '92) and German Mills (then a postdoc in Hoffmann's group and now a professor of chemistry at Auburn University) used a 50-milliliter cell to destroy parathion, a now-banned pesticide. Parathion tends to migrate into water and groundwater, where it lingers. Under natural degradation, half of the dissolved parathion remains after 108 days, according to Hoffmann; its equally toxic metabolite, paraoxon, has a half-life of 144 days. Ultrasound delivering 75 watts per square centimeter at 20 kHz got rid of all the parathion in a saturated solution in two hours. The decomposition products broke down with a half-life of 30 minutes.

Another reactor, used primarily by grad student Inez Hua, has four stainless steel plates that form a rectangular pipe eight centimeters by one centimeter by 100 centimeters long, through which the yucky water flows. The two sets of parallel plates generate ultrasound independently, at different frequencies—a design developed to extract oil from shale. Combining two frequencies gives better results than either one alone, says Hoffmann. "You might set one to 16 kHz, which favors pyrolysis, and the other to a higher frequency, which favors OH radical production." The plates are driven by magnetorestrictive transducers that vibrate in response to a fluctuating electromagnetic field. "This is a particularly efficient setup, because the ultrasound energy is evenly distributed over a large area."

The research group's latest apparatus, run by grad students Ralf Hoechemar, Axel Kratel, Patrick Lang, and postdoc Dean Willberg (PhD '94), is a pulsed-power reactor that uses the discharge from a capacitor bank to zap the water (via a submerged spark gap) with up to 45 kilojoules and up to 25,000 volts at a shot. (At a discharge energy of a mere 12 kilojoules, the group has measured a peak power of 3 million watts, according to Hoffmann.) The blast carries so much juice that the entire $2^{1}/_{2}$-ton apparatus, which includes a power bus the size of an I-beam in a freeway overpass, leaped six inches off the floor the first time they let 'er rip. (It has since been bolted down.) Each 20-microsecond burst explosively vaporizes the water around the electrodes. This forms a rapidly expanding plasma bubble that generates a shock wave packing several thousand atmospheres' worth of pressure. The reflected shock waves cause cavitation. The plasma also fries pollutants directly, as does the ultraviolet light it generates. "In the bulk solution, the reaction pathways are similar to those induced by electron beams, gamma rays, or X rays," says Hoffmann. "We're essentially harnessing the effects of a nuclear explosion." One might call it the neutron bomb of the toxic-waste business. Despite its spectacular mode of operation, this machine may be able to achieve high energy efficiencies, says Hoffmann, who hopes that the pulses will provide more bang for the watt than continuous-power systems can.

Although Hoffmann's lab works on a modest scale, his group has done pilot projects for industry. The clients include drug and electronics manufacturers, both of whose effluents contain complex mixtures of chemicals that are difficult and expensive to treat by other methods currently in use. Some of the chemicals the lab has conquered include triethanolamine, p-aminophenol, and carbon tetrachloride. This latter result implies that ultrasound should be able to treat chlorinated compounds such as TCE and PCE, not to mention PCBs. Hoffmann's lab has even destroyed TNT for the U.S. Army. "Ultrasound is proving itself useful against a wide spectrum of contaminants under a whole range of conditions," says Hoffmann. "It's a very general method. That's the beauty of it—unlike most other methods, you don't have to tailor the treatment process to the details of what you're treating." Even when pollutants run silent, run deep underground, if the water can be brought to the surface, they can be treated. It may even be possible to bolt an ultrasound generator to the wellhead and treat the water in situ. ☐ *—DS*

The Gamma Gambit

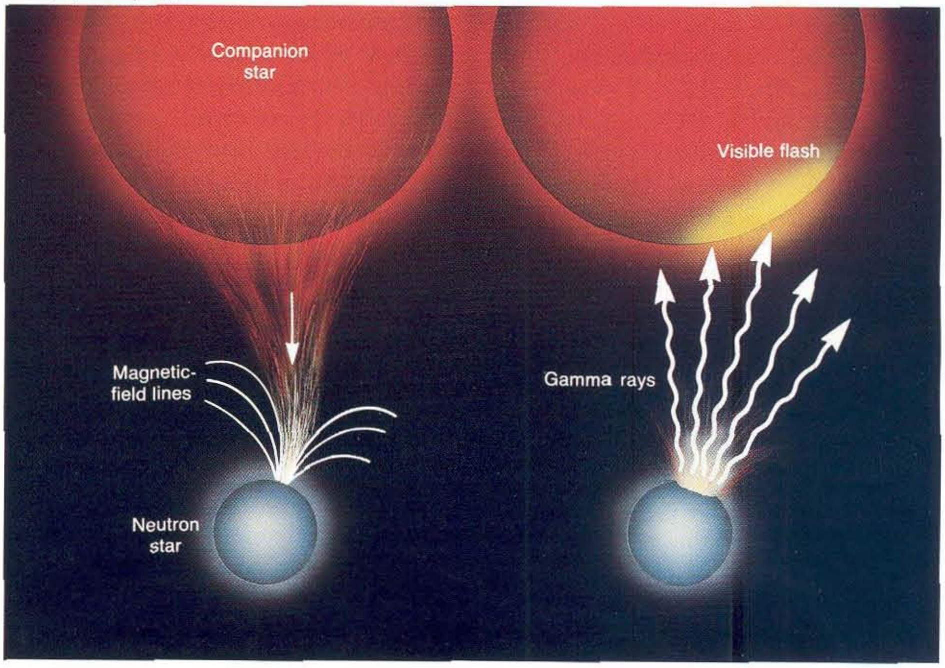
Unseeable from the earth, the neutron star devours its companion, slurping material from the normal star.

In the late 1960s, military satellites on the lookout for clandestine atmospheric nuclear tests discovered something else instead. Like tropical cloudbursts, torrents of gamma rays would suddenly appear, trailing off to background levels in less than a minute. (See *E&S*, Winter 1992.) These celestial outbursts—roughly one per day—don't reach the ground, thanks to the earth's atmosphere. These gamma rays are some of the most energetic astrophysical phenomena ever witnessed, carrying from tens of thousands of eV (electron volts—the energy an electron picks up while traveling across a one-volt potential) up to ten million eV. (For comparison, a photon of visible light has an energy of about two eV.) Ever since the news of their existence was declassified in 1973, astronomers have been trying to figure out where these bursts come from, but telescopic searches of the bursts' apparent points of origin show nothing unusual.

Until the launch of the Gamma Ray Observatory (GRO) in 1991, according to Moseley Professor of Astronomy Maarten Schmidt, astronomers had assumed the bursts came from within our galactic neighborhood. But GRO data show that the bursts come from anywhere in the sky, and never twice from the same spot. (In fact, this is not strictly true—there are three known repeating gamma-ray bursters. Two of these have been identified with supernova remnants—one just this past March, by Professor of Astronomy Shrinivas Kulkarni and colleagues.)

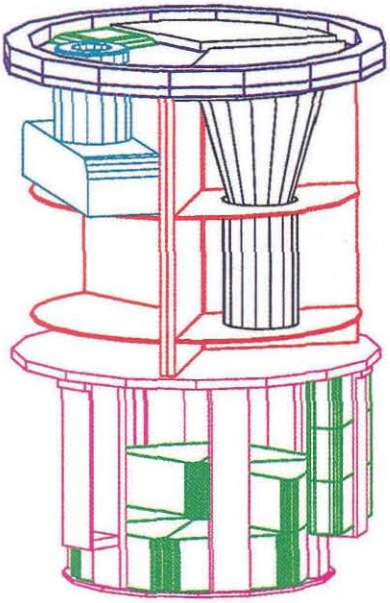
Since the nonrepeating bursts aren't confined to the galactic plane, their sources must either be near enough to lie entirely within the confines of the Milky Way, or far enough away to be outside our galaxy altogether. (The Milky Way is about 2,000 light-years thick and 100,000 light-years in diameter.) Furthermore, the data show that there aren't as many faint bursts as one would expect to see from the observed number of bright ones. This means that the number of sources per unit volume of the universe decreases with distance. That's fine if the sources are extragalactic, but if they're local, it means that we're in a special place in our galaxy where there are lots of sources. Cosmologists don't like this on philosophical grounds—ever since Copernicus dethroned the earth as the center of the universe, scientists have been loath to stipulate that there is anything extraordinary about our galactic neighborhood. "It's a very high-stakes game," says Schmidt. "Either the bursts are a few thousand light-years away, or billions

Courtesy *Sky & Telescope* magazine.



Right: One possible explanation for gamma-ray bursters. A neutron star slowly siphons gas from a companion star. The gas coasts down the magnetic field lines to the neutron star's magnetic pole. Once a critical density accumulates, the hydrogen fuses to helium in a thermonuclear explosion, emitting gamma rays. Some of the gamma rays hit the companion star, where they are absorbed and the energy reemitted as visible light.

Below: GAMCIT's guts. The lid (purple) contains the camera system (blue), GPS receiver (green), and two housings (black) for crystals that scintillate, or emit light, when hit by gamma rays. The superstructure (red) supports the camera and electronics (not shown) and the light cone-photomultiplier tube assembly (black), which captures and records the scintillation light. The battery box (magenta) is filled with battery packs (green), some of which aren't shown for clarity.

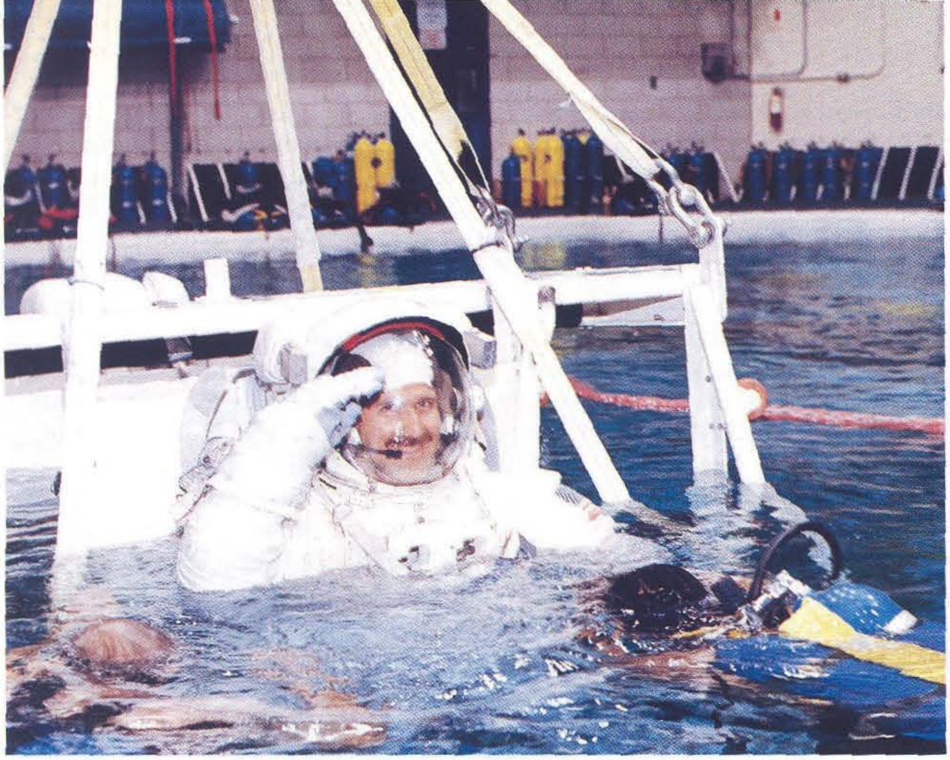


of light-years away. If they're billions of light-years away, they must be from enormously energetic events—perhaps coalescing black holes or colliding neutron stars."

If the bursts are coming from nearby, they could be generated by binary stars that consist of an ordinary star and a neutron star orbiting each other. Unseeable from the earth, the neutron star devours its companion, slurping material from the normal star. The material accretes on the neutron star's surface, where it slowly compacts itself under the star's crushing gravity. The stuff eventually reaches critical density and detonates in a thermonuclear explosion. That would explain why bursts never come from the same spot twice—it takes a good while (perhaps a thousand years) to bunker enough ammunition for a second explosion, and we've only been watching for about 30 years. If this theory is correct, every so often the gamma rays emitted by the explosion should hit the companion star's atmosphere and be reemitted as visible light, causing an optical flash coincident with the gamma-ray burst. However, no one has yet built a detector capable of seeing both at once.

Now, however, some 30 Caltech undergraduates are building a space-shuttle-borne instrument to do just that. The instrument, called GAMCIT, pairs a gamma-ray detector and a 35-millimeter camera. The camera's fixed stare will take in a fair amount of sky as the shuttle orbits. The detector is merely a trigger—when gamma rays hit it, it tells a computer, which must then decide whether a burst is happening. Solar flares also spew floods of gamma rays, electrons, and protons, so GAMCIT carries a charged-particle detector. If the computer logs simultaneous doses of gamma rays and charged particles, it holds its fire. But if the charged-particle detector remains mute, the computer tells the camera to shoot five exposures of one minute each. When the shutter does trip, the computer records the camera's position (but not orientation) to within 10 meters, using data from the Global Positioning System (GPS) satellite network. The computer also records the burst's arrival time, duration, intensity, and energy spectrum from 10,000 eV to 1,000,000 eV.

Once the students retrieve and develop the film, they hope to be able to localize a flash—if they find one—to within one minute of arc. The orientation data comes from the camera itself—each photo should show enough bright, easily recognizable stars to pin down the direction in which the camera was looking. It will take a bit of luck to catch the flash, even if one really occurred, because the gamma-ray detector sees half the sky, but the camera's field of view is



Attended by a retinue *of scuba divers,* astronaut candidate Grunsfeld gives a titanic *salute* as he's lowered into a pool at the Johnson Space Center for weightlessness *training.*

only about 60 degrees wide. The detector cannot pinpoint sources, so the burst's precise location will be determined by other spacecraft.

GAMCIT is what NASA calls a Getaway-Special Canister, or GAScan. GAScans provide a way for small, experimental payloads to be sent into space relatively quickly and cheaply. Thus undergrads can design, build, and fly a real payload—and analyze the data from it—in less than the time it takes to graduate. (About 100 GAScans have flown to date.) At $19^3/_4$ inches diameter and $28^1/_4$ inches high, GAScans are bigger than wastebaskets but smaller than oil drums, and can hold 200 pounds each. They get stowed in odd corners of the shuttle's cargo bay as a mission's size and weight requirements permit. They are self-contained and self-sufficient—GAMCIT gets its juice from 282 size-D batteries. All the astronauts do is open the shuttle's cargo-bay doors and then flip three switches that open the canister's lid and turn on GAMCIT's electrical systems. The switches are in the crew compartment, so no one even lays a glove on the canister.

The students hope to fly GAMCIT on Astro 2, a two-week mission whose main payload is an astronomical observatory containing three ultraviolet telescopes. Astro 2 is currently set for launch in January, 1995, on the space shuttle *Endeavour*. And although the shuttle crew isn't supposed to have anything to do with the GAScans, one member is going to be pulling hard for this one—mission specialist John Grunsfeld, who will be making his maiden flight. Grunsfeld was a gamma-ray astronomer at Caltech's Space Radiation Lab before matriculating at astronaut school in 1992.

While at Caltech, Grunsfeld was the faculty advisor for the campus chapter of SEDS (Students for the Exploration and Development of Space—an international organization). He resuscitated Caltech's GAScan program, which had lain in a coma for a decade, by originating the GAMCIT project. Caltech's Student Space Organization (SSO), now defunct, had reserved four GAScan slots in the early 1980s, according to Grunsfeld, but SSO's first and only payload flew in 1984. It blew its main fuse upon reaching orbit, and that was all she wrote.

That's one bit of history that should not repeat itself. Daniel Burke, the electronics design engineer for Caltech's high-energy physics group, is GAMCIT's technical advisor. "He's given us a lot of advice and help in the design of the electronics," says Albert Ratner, a junior in mechanical engineering. Burke, who has known Grunsfeld since the days when both worked in the Space Radiation Lab, tries to stay in the background, saying, "My primary role is one of support, rather than actually designing or building. This is a bit awkward at times, since the urge is to simply take over and do the work. Restraint is required in order to allow the students to make some mistakes, develop their own initiative, and generally understand how things happen outside the artificial classroom environment. But it *will* be a functional instrument upon completion; we (the advisors) have a significant amount of experience in doing such projects."

Electrical failures notwithstanding, the thermometer is a GAScan's worst enemy. Allen Burrows, of JPL's environmental testing group, has helped the undergrads put GAMCIT's components through an exhaustive thermal program. "That's the single most common source of failure in GAScans," Ratner says. "They freeze or they burn, either at

From left: Ratner, McCall, Burke, and junior Bridget Mattingly have the GAMCIT component situation in hand. McCall holds the mold for the light cone. Mattingly holds one of 24 triangular assemblies that contain 10 D-sized batteries each. And Ratner holds the shipping container in which GAMCIT will journey to Goddard. Note that the shipping container also has a lid that NASA doesn't call a lid—it's a Reuseable End Plate.

the Cape or in space." Ratner and Eric Wemhoff, a senior in mechanical engineering, have done a comprehensive thermal analysis of the whole experiment for a course they're taking in heat transfer and thermal design. A cold snap at Canaveral is certainly a possibility in December, Ratner admits, but GAMCIT should be unfazed—after all, you keep film and batteries fresh by storing them in the fridge, and GAMCIT's electronics have been tested to −10° F. On the sunny side, everything works fine up to about 150° F, at which point the computers begin to get unhappy.

You don't just stroll into Kennedy Space Center with a hunk of machinery and say, "Here. Fly this." Grunsfeld and a small group of students began filing GAMCIT's preliminary paperwork sometime around 1990. Getting into the government mind-set has been an experience in itself. For example, GAMCIT's lid—a steel plate with a quartz window that keeps the can pressurized while allowing the camera to see out into space—is now a UDMD, or User-Designed Mounting Disk. "We called it a lid, and they flipped," Ratner recalls. "They said, 'People will confuse it with our lid.' It was so much more worth it to call it a UDMD than to have people be confused." (GAMCIT will ride in a NASA-supplied canister that also has a lid, you see. But, in fact, NASA doesn't call *its* lid a lid, either—it's a Motorized Door Assembly, or MDA.) As for navigating the flight-certification labyrinth, "If I actually call them and ask a specific question, they're fine. They'll explain everything. But in getting stuff to us in advance, in explaining requirements, in volunteering information, they've been really bad. I mean, I'm not psychic." Even so, GAMCIT had its Final Safety Package approved on January 14, 1994, which means that NASA is satisfied that GAMCIT won't explode, catch fire, or otherwise injure the shuttle. (Ratner spent Christmas Day doing stress analyses for the certification.)

Now that the design has been okayed, it's time to start construction. The GAMCIT team has tested most of the components. The large-scale machine drawings from which the flight hardware will be fabricated are pretty much finished, too. Assuming Astro 2's date with the stars doesn't slip and the god of payload assignments smiles, GAMCIT will be assembled during July. Two or three people will drive it to Goddard Spaceflight Center in Maryland in the ASCIT van in August (road trip, anyone?). The Goddard folks will put it in its actual flight container, test it for electromagnetic interference to be sure it doesn't jam some vital shuttle system, pressurize it with nitrogen, seal it, and ship it off to the Cape.

But that's all down the road. At present, the GAMCIT team is still shopping for parts. Buying GAMCIT's skin and bones—stainless-steel stock, Kevlar sheets, and heavy-duty epoxy cement—will be fairly easy. Acquiring its guts and brains on SEDS's shoestring budget has been more challenging. For example, the 35-millimeter film magazine that holds the roll of 250 exposures costs $5,000—more than the camera itself, which is "only" $3,000. SEDS president Benjamin McCall, a junior in chemical physics, is still working on that one, but companies have been coming through with much of what's needed. Intel, for one, donated GAMCIT's microprocessor brain, plus a 386 computer and a host of supporting equipment for the design effort. Says Ratner, "Intel has been more than generous, and they've been just beautifully fast. They're angels." Some of the other sponsors include Rocketdyne, which provided $2,500 in start-up funds; Trimble Navigation, which contributed the GPS unit; Hewlett-Packard, which lent the project some $20,000 dollars' worth of oscilloscopes and other testing equipment; and Intégral Peripherals, which supplied the hard disks on which GAMCIT will record all its data. And just recently, Duracell agreed to donate the batteries.

Of course, there's no guarantee that GAMCIT's data will solve the riddle of the bursts' origins, but that's life. "These are the most mysterious objects in astronomy right now," says Schmidt, who became faculty advisor to the GAMCIT team after Grunsfeld's departure for the Johnson Space Center. "I can think of no other object where the uncertainty in distance is a factor of a million." ☐ *—DS*