Making Stars
High-tech ‘Thor's Hammer’ forges extreme environments
STAR IN A BOTTLE
Astronomers study test-tube stars created by the world's most powerful X-ray machine

Electricity arcs across the Z machine during one of its shots.
By Damond Benningfield
ith a flash of lightning and a chest-squeezing bang, a star is born. It will live for only a tiny fraction of a second before it cools and fades. Yet in that flicker of cosmic time it will help astronomers understand the final stage of life of most stars, which in turn will help them better understand all of cosmic time, from the age of the universe to its fate.

This star isn't of the big, round, shiny variety, though. Instead, it's a beaker of hydrogen gas the size of a bratwurst that's instantly heated to temperatures hotter than the surface of the Sun, ripping the hydrogen atoms apart to form a state of matter known as a plasma.

During its brief life, this faux star is a perfect replica of conditions in the thin atmosphere of a white dwarf, the crushed corpse of a once-normal star like the Sun. "It's not like the conditions in a white dwarf plasma, it is the conditions in a white dwarf plasma," says Don Winget, a University of Texas at Austin astronomer and, with colleague Mike Montgomery, lead scientist for the experiment. Winget and colleagues will compare the plasma to that observed in more traditional white dwarfs — those sprinkled through the universe — to refine the models of how these stellar remnants behave. White dwarfs play key roles in determining the age of the galaxy and measuring the effects of dark energy, so it's critical for astronomers to understand their nuances.

For that, they venture to Building 983 at Sandia National Laboratories, a national security research center on the western flank of the Manzano Mountains in Albuquerque. Like many of the buildings around it, the warehouse-like structure is painted desert tan. Unlike most of Sandia's other buildings, however, this one has a name over the front door: Z Pulsed Power Facility.

It contains the world's largest sparkmaker, a tank more than 100 feet in diameter and two stories tall known as the Z machine, which generates brief but intense bursts of power that produce high temperatures, strong magnetic fields, and intense pressures.

Z's primary mission is to help maintain America's nuclear weapons arsenal, but some of its time is devoted to fundamental science, allowing researchers to probe some of the most extreme conditions in nature, from the surfaces of white dwarfs to the cores of giant planets. "Z uncovers things about nature that people didn't know were there," says Greg Rochau, research and development manager for the Z facility. "There's always a surprise when you do a Z experiment."

That's because the machine is like nothing else on Earth. It provides extreme conditions on a grand scale, allowing researchers to study samples that are far larger than those in any other laboratory facility — from the size of a grain of sand up to the bratwurst-size hydrogen container. Although that sounds minuscule by everyday standards, to a physicist it's a big blob. "What's different about Z is that the quantities of material we're heating to these conditions are much larger than ever before," says Jim Bailey, distinguished member of the technical staff at Sandia, who works on several Z experiments. "So we're not just reaching these conditions, but we're doing it with a large amount of material for a long time under uniform conditions."

Z achieves those conditions through brute force — a sort of Thor's hammer of the extreme-physics world.

The heart of the machine is a set of 36 electric capacitor banks arranged like the spokes on a wagon wheel. Z draws electricity from the local power grid — enough to light about 100 houses for a few minutes — and stores it in these devices.

When all systems are "go," the capacitors fire together in a controlled short-circuit: all 36 discharge within 10 billionths of a second, sending their power racing toward the center of the machine, a vacuum chamber 12 feet in diameter. The power is compressed in steps, then discharged to the experiment chamber. This jolt carries more than 1,000 times the electricity of a typical lightning bolt, but it discharges much faster — less than a millionth of a second. In that instant, it can produce up to 85 million megawatts of power, "far more than the entire electrical capacity of the entire world," says Joel Lash, the Z facility's senior manager for research and development.

All of that energy is channeled into a small target capsule. The one for the white-dwarf experiment and several others conducted in the same shot contains a network of hundreds of tungsten wires, each about one-tenth the diameter of a human hair. The energy pulse

A wire-mesh target is ready for a shot. The wires are much thinner than a human hair.
vaporizes this “cage” of material with the force of 10 pounds of dynamite, creating a terrific concussion. “You can feel the Earth shake when the machine fires,” says Lash.

A powerful magnetic field surrounds the vaporized material, forcing it to slam together along the container’s vertical axis (the “z” axis in the three-dimensional x-y-z coordinate system, which is where the Z machine gets its name). That creates a shockwave that runs into more material that is falling inward. This collision heats the material to roughly the same temperature as the interior of the Sun, producing enormous amounts of X-rays. “It makes a fantastic X-ray light bulb,” says Bailey.

The X-rays shine through small openings in the chamber, irradiating the beaker of hydrogen and other samples at distances of roughly 2 to 12 inches (5-35 cm), converting them to a plasma — a state in which an atom’s electrons are ripped away from its nucleus. These samples are recorded by high-speed cameras and other instruments. Scientists analyze these readings to determine how the sample materials behave, providing a better understanding of extreme environments.

“We try to understand these environments with models and computer codes, but they’re so incredibly complicated that it’s hard to vet them,” says Taisuke Nagayama, a postdoctoral researcher at Sandia who is studying the effects of impurities in the outer layers of the Sun. “Now that we can study these conditions in the lab, we can test the models under realistic conditions and see which are most accurate.”

On a brilliant Monday in late September, Z is being prepped for firing No. 2,552, a process that resembles the countdown for a space mission. It takes a day or more for a team of several dozen engineers and technicians to ready the machine for a single shot.

Much of their time is devoted to cleaning. Any impurities in the machine can divert some of Z’s electrical discharge, reducing the effectiveness of the experiments and perhaps damaging the equipment. So bunny-suited technicians wipe down the walls of the central vacuum chamber as well as a large cone that will contain the samples for another day’s experiments.

As they work, a man in a wetsuit walks along the catwalks that crisscross the top of the machine, preparing to dive into the innermost of two rings around the vacuum chamber. The rings contain fluid to insulate the giant capacitors and the other electrical equipment. The outermost ring holds about a million gallons of transformer oil (the smell of which permeates the building), while the inner ring contains about a half-million gallons of ultra-pure water. Divers check for air bubbles, which could short out the system.

As the Sandia team prepares the Z machine, researchers from several institutions prepare their experiments. They are members of a collaboration known as ZAPP (Z Astrophysical Plasma Properties), which compares plasmas created by Z to those seen in the universe.

Ross Falcon, a University of Texas graduate student who works at Sandia full time on the white dwarf project, prepares the hydrogen gas cell. Also wearing a bunny suit, he works inside a restricted area where signs warn of possible contamination by beryllium, a material that can produce health problems.

“The experiments are really difficult,” he says. “If you miss one little thing, it can collapse your whole data set. If an optical fiber gets pinched in installation or you forget a connection, you see nothing. ... One of the first lessons I learned was that double checking isn’t good enough — you need to triple check.”

One experiment will use a thin wafer
of silicon sandwiched between layers of plastic to shed new light on the accretion disks in X-ray binaries, in which gas from a "normal" companion star spirals toward a black hole a few times the mass of the Sun. The gas is heated to millions of degrees, so it emits copious X-rays. Observations by space-based X-ray telescopes don't match some of the accretion disk models, though, so the Z experiment should help astronomers better understand the physics of these disks.

Another experiment will use iron and magnesium to shed new light on a possible problem with models of the Sun and other stars.

"Until about 2000, the best astrophysical models of how the Sun works matched the observations," says Jim Bailey, who leads the experiment. Observations in 2000, however, found that the amounts of certain elements in the Sun's atmosphere were far off those found by earlier work. These elements make up only a tiny fraction of the Sun's total mass, which is almost entirely hydrogen and helium, but they play a major role in the way energy is transported from the Sun's core, where the energy is generated, to its surface. "The dilemma is the best models don't match the best observations," Bailey says, although he notes that many astronomers reject the troublesome observations.

Some researchers have suggested there could be a flaw in the models of how much energy the trace elements block or let through, known as their opacity, observations are flawed or incomplete, or, more distressingly, that models of how stars work are off.

"We've been working for the last five years to produce the right conditions, and we're close to being ready to publish our results. We're still scrutinizing our analysis — we're checking the math before publication," Bailey says with a chuckle. "None of this has ever been done before."

As he speaks, technicians are working on a problem with the day's shot. A leak has developed at the top of the vacuum chamber. They ponder possible solutions with Greg Rochau, including using a sealant to plug the leak. After some quick discussions, though, they decide to scrub the shot. The Sun has set on today's attempt to better understand the workings of our star. But it will rise again tomorrow, bringing another chance to shake the world.

Ross Falcon had started his graduate work at the University of Texas when Jim Bailey visited the Austin campus. Falcon was studying white dwarf stars with Don Winget, using data gathered with telescopes at McDonald Observatory and elsewhere. "I didn't even know what Sandia was," Falcon recalls. "But Jim talked about the work they were doing with the Z facility, the conditions he was reaching there, and he said that maybe we could create the conditions of a white dwarf atmosphere."

Texas soon joined the ZAPP collaboration, and Falcon began working with Bailey and Greg Rochau to design the white-dwarf experiments. The first test shot took place in April 2010, and the following year Falcon moved to Albuquerque to work on the project full time while he completes his PhD.

On the second day of this set of experiments, with the first of five scheduled shots already lost to technical problems, he's completed his pre-firing preparations, with the gas cell in the vacuum chamber at the heart of Z. The cell, which has evolved over the course of the project, is 12 centimeters long and about two centimeters wide (4.5 x 0.8 inches). X-rays will shine into the cell through a mylar window and hit a gold backplate, which will heat up and radiate energy into the gas, stripping the electrons from the protons to form a plasma. Fiber-optic lines will carry observations of the glowing plasma to the scientific instruments, allowing Falcon and his colleagues to study the results in detail.

The project is of particular interest because white dwarfs are handy tools for many astronomical endeavors, including measuring the age of the Milky Way galaxy and plotting the effects of dark energy.

A white dwarf is born when the nuclear reactions in a Sun-like star come to an end. Throughout its long life, the star fuses the hydrogen in its core to make helium, then fuses the helium to make carbon and oxygen. But the core can't get hot enough to fuse the carbon and oxygen, so its nuclear engine shuts down. The star's outer layers puff out into space, while the core shrinks to roughly the size of Earth. Although it no longer generates energy through nuclear fusion, the core is extremely hot, so it will continue to shine for billions of years.

Because white dwarfs are the endpoint for Sun-like stars, they can tell astronomers much about how stars evolve and die. And the surfaces of some older white dwarfs pulse in and out like a beating heart, creating sound waves that ripple through the star and back to its surface. Measuring these ripples can reveal the white dwarf's structure.

But white dwarfs also serve other scientific purposes. For one, they are good "cosmochronometers" — devices for measuring cosmic time. "A white dwarf is really simple — it evolves simply by cooling," says Winget. "So you can determine its

'Z uncovers things about nature that people didn't know were there. There's always a surprise when you do a Z experiment.'

— Greg Rochau
age by taking its temperature. If you find the coolest white dwarfs, you can use that to measure the age of the galaxy.” And since the universe can’t be older than its oldest stars, measuring the oldest white dwarfs provides a good check on the age of the universe measured with other techniques.

White dwarfs also contribute to the study of dark energy, a mysterious force that is causing the universe to expand faster as it ages. If a white dwarf of a particular class steals enough hot gas from the surface of a companion star, it can explode as a supernova. Current models say that all of these blasts should be equally bright. “We use these as standard candles,” says Thomas Gomez, another Texas graduate student working at Sandia. “We see how bright they appear versus how bright we expect them to be, which tells us their distance. We then use those to measure the expansion of the universe at different times.”

All of these uses, however, require precise knowledge of conditions at the surface of a white dwarf—something that still needs improvement, says Winget, who’s been studying white dwarfs for the last 35 years.

Indeed, some models, which infer a white dwarf’s mass from its gravitational effect on the light it radiates into space, have given results that completely disagree with the masses derived from other techniques. And even small errors in the understanding of white dwarf surface conditions could produce big errors in their masses, ages, and other parameters, Winget says. And that’s where the Z machine experiments come in. The current tests focus on a class of white dwarfs that are about two-thirds as massive as the Sun. Although they consist mainly of carbon and oxygen, they are surrounded by a thin atmosphere of hydrogen.

“Hydrogen is the simplest and most abundant element, so surely we know all about that,” says Winget. “And that’s true if it’s a little hydrogen atom standing out in space by its onesie. But put it together with a lot of others, mix it up, and we still don’t have it right...So we decided, let’s benchmark the surface plasma conditions, which affects everything you do with a white dwarf star.”

More than three years and 30 shots into the project, that work continues. In fact, by the middle of Tuesday afternoon, the first shot of the week is finally ready to go. Falcon, Gomez, and others gather outside a set of double doors to watch it happen. Control room technicians count up as the voltage builds inside Z’s capacitors. Finally, after almost two full days of preparations, the lightning flashes, the building shakes, and the computers record the results — the instant birth, brief life, and quick demise of a star in a gold-lined bottle.

Damond Benningfield is executive editor of StarDate magazine and writer/producer of the StarDate radio program.

Resources

Internet
Z Pulsed Power Facility
www.sandia.gov/z-machine
The Art and Science of Making White Dwarfs in the Desert
web5.cns.utexas.edu/news/2012/08/white-dwarfs-in-the-desert
Don Winget: Astronomy and Horses
mcdonaldobservatory.org/research/astronomers/winget