ASTROPHYSICS

Ashes to Ashes: The Inner Lives of Neutron Stars

"Superbursts" that rage for hours within certain neutron stars might drive exotic thermonuclear reactions unique in the universe

CHICAGO, ILLINOIS—Steamboat Geyser, in the heart of Yellowstone National Park, usually shoots fountains of water 5 to 10 meters high. But at irregular intervals of years to decades, the geyser unleashes a scalding 100-meter column, followed by a deafening roar of steam for a day or more. A mysterious trigger far underground expels the deepest, hottest water from the geyser's hydrothermal system in a crowd-pleasing burst.

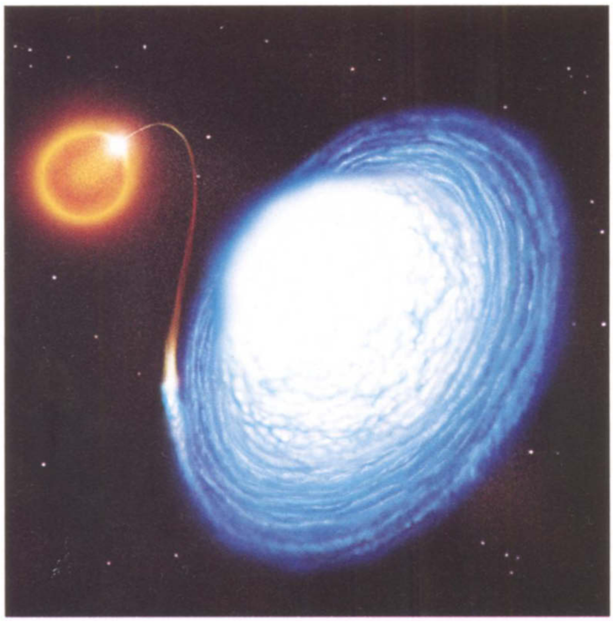
Similar outbursts happen in space, astrophysicists have learned. Powerful and unpredictable flares of energy, given the geyserlike name of "superbursts," strike beneath the surfaces of a few special neutron stars—the dense, spinning corpses of stars that died in supernova explosions. Orbiting telescopes have spotted seven superbursts so far, spouting intense x-rays for hours. Even more compelling than the fireworks is the root cause: a thermonuclear flash of heavy elements, burning in ways that might occur nowhere else.

Superbursts happen only in tight binary pairs, where a neutron star pulls gas from the outer atmosphere of a small companion. Under certain conditions, a layer of the gas—usually hydrogen and helium—can build up on the neutron star's surface. Every few hours or days, this raw nuclear fuel spontaneously combusts in about 10 seconds. Astrophysicists first spotted these "type I x-ray bursts" in the mid-1970s and explained them as thermonuclear fusion run amok.

A quarter-century later, it turns out the story doesn't end there. A modest type I burst creates "ashes" in the form of heavy atomic nuclei, which settle into a dense ocean covering the entire star. When the pressure and temperature at the bottom of this bizarre ocean get high enough, the ashes themselves ignite. The thermonuclear flame explodes into a superburst that spews 1000 times as much energy into space as a type I burst. According to models, the inferno burns the entire 100-meter-thick ocean of heavy ashes.

When x-ray satellites first caught these jaw-dropping events a few years ago, some astrophysicists thought pure carbon fueled the flame (*Science*, 17 November 2000, p. 1279). However, new calculations suggest that although carbon is indeed the spark, most energy in a superburst comes from far heavier elements that literally disintegrate in a 7-billion-kelvin bath of gamma rays.

"We sometimes get lulled into believing that we've seen it all in astrophysics, then nature comes up with something new and amazing," says physicist Robert Rosner, director of the Department of Energy's Center for Astrophysical Thermonuclear Flashes, or Flash Center, here at the University of Chicago. "Superbursts are extraordinary. To many of us, they seem like science fiction."



Shattered disk. X-rays from a thermonuclear "superburst" might blow apart the disk of gas that girdles a neutron star in a tight binary system.

ILLUSTRATION: C. SLAYDEN

Small potatoes

In the panoply of cosmic things that go boom, superbursts are impressive but not ascendant. "In comparison with gamma ray bursts and supernovas, these are small potatoes," says astrophysicist Edward Brown, a postdoctoral researcher at the Flash Center. Type Ia supernovas—the kind used to gauge the accelerating expansion of the universe—release a billion times as much energy and shine across billions of light-years. Satellites have spotted superbursts only within the cozier confines of our Milky Way galaxy.

Superbursts excite astrophysicists not for their absolute power but for their potential to reveal how matter is transformed by pressures and densities just a whisper shy of a black hole. Neutron stars pack about 1.5 times the mass of the sun into a sphere just 20 kilometers wide, only three times the size of a black hole of the same mass. "On a neutron star, gravity completely has the upper hand," says astrophysicist Don Lamb, also a member of the Flash Center. Indeed, gravity's clamps are so strong that the energy created by thermonuclear burning barely budges the matter above it. "Once burning starts, the pressure rises and there's no way out; it can't find a stable equilibrium," Lamb says. "It runs away and burns everything that has been accreted."

Hydrogen and helium cascading onto a neutron star from a companion can burn in two ways. In stable burning, the gas combusts just as quickly as it hits the star, like the steady blue flame on a natural gas stove. In unstable burning, not enough gas arrives to keep the flame going. The gas builds up and then ignites with a poof, enveloping the whole star in less than a second with a type I x-ray burst.

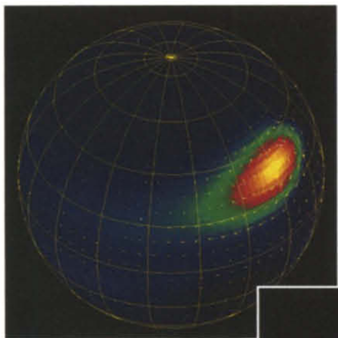
For years, researchers thought these processes would forge a lot of carbon—especially helium burning, which cooks carbon efficiently. Stripped of their electrons in the extreme conditions, the nuclei of carbon atoms would settle into an ever-deepening ocean beneath the ongoing hydrogen-helium bursts. Papers predicted that thermonuclear flashes could happen in that ocean. However, calculations showed that it might take hundreds or thousands of years to build up enough carbon for the pressure to cross its higher ignition threshold. No one expected to get lucky enough to see such an event.

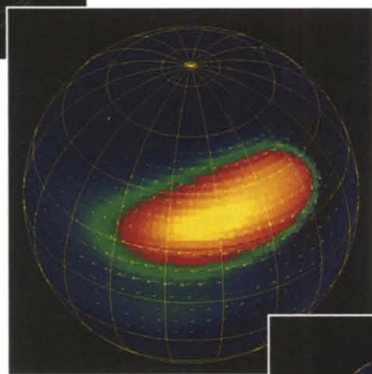
Then, starting in 1996, superbursts began popping up. Astronomers at the Space Research Organization Netherlands in Utrecht found the first one—originally dubbed the "Oh my God!" burst—with the Dutch-Italian satellite BeppoSAX, which flew for 6 years. Teams led by astronomers Erik Kuulkers, John Heise, and Remon Cornelisse have since found a few more by scouring data from a wide-field camera on BeppoSAX that gazed toward the center of the galaxy for months at a time.

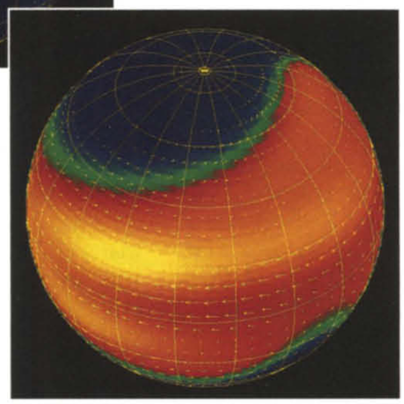
Astronomer Tod Strohmayer of NASA's

Goddard Space Flight Center in Greenbelt, Maryland, also struck pay dirt twice with fortuitous observations by NASA's Rossi X-ray Timing Explorer, still active after 7 years. One of those discoveries revealed that the same binary system had spawned a pair of superbursts 4.5 years apart. Clearly, it didn't take 1000 years to replenish the superburst fuel on that neutron star.

Once observers showed that superbursts are far more common than expected, theorists were forced to reconsider the mixture of ashes left over from type I x-ray bursts. First, a team led by nuclear physicist Hendrik Schatz of Michigan State University, East Lansing, did a thorough calculation of the reaction products of hydrogen flash fusing on a neutron star.







Nuclear storm. Flash ignition of hydrogen and helium on a spinning neutron star might spread in a hurricane-like pattern. Carbon-powered superbursts ignite a far deeper layer.

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The results, in the 16 April 2001 *Physical Review Letters*, showed a slurry of massive nuclei up to tin, antimony, and tellurium (atomic numbers 50 to 52). At that point, a closed cycle of element creation and destruction prevents heavier nuclei from forming. Even so, exotic elements such as krypton and ruthenium should churn into the dense ocean with the carbon from helium burning.

Second, postdoctoral researcher Andrew Cumming and physicist Lars Bildsten of the University of California (UC), Santa Barbara, realized that those ashes would change the fluid's key properties. Heat flows easily through an ocean of pure carbon nuclei, making it hard to build up hot spots and ignite a spark. With heavy elements, "the ocean becomes more opaque, so heat can't escape as quickly," says Cumming, now at UC Santa Cruz. "You can ignite a flash much sooner with less material." The study, in the 1 October 2001 *Astrophysical Journal Letters*, predicted that an ocean containing just 5% to 10% carbon would suffice to trip the thermonuclear trigger every few years.

Nuclear weirdness

As for the prodigious energy spewed by the events, new research by Schatz and his colleagues points to another surprise. After the flash fusion of carbon nuclei gets a superburst started, it might play only a supporting role.

The team's work, still in progress, suggests that temperatures soar to 7 billion kelvin in the first microseconds of the runaway burst. In those searing conditions, an intense bath of gamma ray photons bombards nuclei like shotgun pellets blasting a boulder. The onslaught chips neutrons and protons off the heavy nuclei and reduces their mass, a process called photodisintegration. "We all overlooked the fact that it gets hot enough to start this other process," Schatz says.

The effects of photodisintegration are dramatic. Iron (atomic number 26) is the most stable nucleus. Smashing bits off massive nuclei and transforming them into iron yields energy as each nucleus becomes more tightly bound. Depending on the mixture of heavy ashes in their modeled neutron-star oceans, Schatz and his co-workers are finding that this violent sputtering produces far more energy than the fusion of carbon and other lighter nuclei.

"If you look at all the sites in the universe where nuclear processes happen, this would be the only case where photodisintegration is the dominant energy source," Schatz says. "It's a weird process that generates much more energy and happens much faster than we expected."

Much of the superburst's energy dives into the neutron star's colder interior. The rest takes hours to diffuse through the thick ocean and blast into space. Above the neutron star's surface, the intense x-rays might destroy part of the disk of gas from the companion star. Strohmayer hopes to scrutinize superburst records for clues about how the disk reassembles.

Verifying other aspects of superbursts—especially the details of how they transform matter—will be more challenging. Unlike a supernova, which propels its freshly made elements into space for telescopes to detect, neutron stars horde it all. Virtually nothing escapes. "It's like a black hole in its shyness," says Lamb. It's barely possible that some heavy ashes might convect to the neutron star's surface long enough for future x-ray or gamma ray telescopes to probe.

What's the trigger?

With just a handful of superbursts identified, other mysteries are keeping physicists busy. The frontier, says Bildsten, is that no one knows what sparks the flash. In some cases, a type I x-ray burst precedes the superburst, leading some scientists to propose that the surface flash of hydrogen and helium fusion triggers the deeper event. Bildsten considers that unlikely. "It's like sitting at the bottom of a 10-kilometer-deep ocean and asking, 'Do I care what the weather is at the surface?' " he says. "The scales of pressure are that different."

Researchers also debate whether ignition occurs nearly everywhere on the star at once, as Lamb believes, or whether it starts at one point and then spreads. Type I bursts might yield a clue. A model by astrophysicist Anatoly Spitkovsky of UC Berkeley and his colleagues suggests that the breakneck spin of a neutron star in a close binary—typically hundreds of rotations each second—distorts the initial flame of a type I burst into a lopsided hurricane, thanks to the strong Coriolis force. That storm then expands quickly around the star's equator.

Observations of both type I bursts and superbursts show rapid oscillations that Strohmayer and Bildsten interpret as a hotter spot rotating in and out of view. However, the oscillations last far longer than it should take for the flame to travel evenly around the star. Nor do researchers know how quickly the ignition might spread for the deeper superbursts, where conditions are far harder to model.

Despite all the unknowns, theorists agree on what *not* to expect: We shouldn't hold our breath for a super-superburst. "Superbursts are the last step for explosive ignition," says Cumming, because their ashes consist largely of stable iron. Deeper inside a neutron star, he notes, further reactions will squeeze nuclei together into a true ball of neutrons, gradually releasing energy. The end result, just a few kilometers down but forever inaccessible, consists of matter crushed as close to oblivion as one can get without vanishing into a black vortex.

–ROBERT IRION