ASTROPHYSICS

How Collapsing Stars Might Hide Their Tracks in Black Holes

Where have all the neutron stars gone? As many as 150 shells of gas and dust left by the recent collapse and explosion of massive stars litter our galaxy, and the standard wisdom predicts that each of them should hold a dense cinder, or neutron star. But fewer than two dozen of these supernova remnants have revealed neutron stars. The most notorious absence involves the great supernova of 1987. Under all standard stellar evolution scenarios, a pulsar—a radio-emitting neutron star—should have shown itself by now in the debris of this supernova, the brightest in 400 years. Yet none has been found.

Now Hans Bethe of Cornell University—the renowned physicist, still productive at 87—and Gerald Brown of the State University of New York at Stony Brook have proposed a new way of accounting for the missing neutron stars: gone to black holes every one. Astrophysicists have long thought that only the very largest stars could collapse all the way down to black holes. But in a paper to be published in the *Astrophysical Journal*, Bethe and Brown argue that even run-of-the-mill supernovas, in stars having only 18 to 30 times the mass of the sun, could create black holes.

CHARLES J. HARRINGTON/ CORNELL

Dark vision. Cornell astrophysicist Hans Bethe.

"If their theory is really right," says Shri Kulkarni, an astronomer at the California Institute of Technology who has read the paper, "it's pretty profound." It would imply that the galaxy harbors as many as a billion "small" black holes, measuring a few kilometers in diameter. The theory also has implications for the cinders left when stars of less than 18 solar masses collapse. It suggests that they leave behind not neutron stars but composites of neutrons and protons (nucleons) that should properly be called nucleon stars—though they would appear the same as neutron stars to Earthbound observers.

Traditionally, astrophysicists have envisioned two ways for a star weighing more than 8 solar masses to end its life. In both cases, the star's fate is sealed when nuclear burning in its core converts the last of its fuel into iron. When the iron core grows to between 1.5 and 2 solar masses, it can no longer sustain itself against gravity, and it collapses. If the core weighs less than 1.8 solar masses, as it will in a star of less than 30 solar masses, the collapse ends abruptly when the core has formed a neutron star—in essence, a giant ball of neutrons. The jolt apparently generates a shock wave, which blows off the remainder of the star. The result is a Type II supernova, with a neutron star left over. (Type I supernovas occur in white dwarf stars and leave no remnant.)

In a progenitor star that has a mass greater than 30 times that of the sun, the core grows to 1.8 solar masses or more before collapsing, and the collapse doesn't stop with the formation of a neutron star. In a matter of milliseconds, the massive star vanishes into a black hole. As Brown puts it, "The whole mass of the star just goes poof, straight into a black hole." Thus, as far as most astrophysicists were concerned, a massive star could end its life either as a supernova and a neutron star, or as a massive black hole—without a supernova.

But the surplus of supernova remnants over neutron stars left some researchers wondering whether there might not also be a third way for a star to terminate its life: by lingering at the neutron star stage for long enough to trigger a supernova, then vanishing into a black hole. In 1986, for example, Stan Woosley of the University of California, Santa Cruz, and Jim Wilson and Tom Weaver of the Lawrence Livermore National Laboratory suggested two scenarios for such "hit-and-run" supernovas. One applied to large stars (more than 30 solar masses): The stellar core, though massive enough to form a black hole, would temporarily stop collapsing when it had formed a neutron star because the thermal energy of the collapsed material would generate too much pressure for the collapse to continue. After the neutron star had cooled, it would collapse to a black hole. In the other scenario, the collapse would yield a neutron star at first, but star material blown out by the explosion would later fall back onto the neutron star, pushing it over the threshold for further collapse.

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Still no pulsar. A neutron star, the expected relic, still hasn't turned up in the debris of Supernova 1987A (bright spot at right).

Having suggested these notions, however, Woosley, Wilson, and Weaver never pushed them with any vigor. When Brown and Bethe learned of them this spring after developing their own scenario, they agreed with the end point, supernovas and black holes from the same star, but offered a different mechanism. It is built on a new equation of state for the matter inside a collapsed star—a mathematical description of how it responds to pressure—that implies "softer" material than theorists had pictured.

Because the nuclear matter provides less outward pressure for a given density, the new equation of state allows a massive star smaller than 30 solar masses, with a core as small as 1.5 solar masses, to collapse all the way into a small black hole. The collapse doesn't go off without a hitch, though: It pauses at the collapsed star stage for as long as 20 seconds, long enough to launch a supernova on its way. That would allow astrophysicists to have their supernovas without worrying about the lack of neutron stars. "Without our equation of state," Bethe said, "we would have said that whenever you get a [Type II] supernova the massive object left behind should be a neutron star. This we now no longer believe."

The new equation of state reflects Brown and Bethe's picture of how subatomic particles behave during the collapse at the end of a massive star's life. Astrophysicists have assumed that when a stellar core collapses, all the electrons in the core are captured by protons, which emit neutrinos and become neutrons—hence the term neutron star. But last year, Brown and several colleagues suggested that the electrons in a collapsing core might meet a different fate. As the core reaches a density three times that of nuclear matter, they proposed, it becomes energetically favorable for electrons to turn into negatively charged k mesons, or kaons (particles consisting of a strange quark paired with a down quark) and emit neutrinos in the process.

Because the protons don't absorb the kaons as they would electrons, the protons remain protons rather than turning into neutrons. The result is a mixture of protons and neutrons steeped in what's called a kaon condensate, a state of matter described first in 1986 by David Kaplan and Ann Nelson, then junior fellows at Harvard, and in more detail in 1991 by David Politzer and Mark Wise of Caltech. And because the attraction between protons and neutrons is stronger than between neutrons and neutrons, the collapsed material is more compressible than theorists had previously assumed—and easier to squeeze down into a black hole.

The collapse into a black hole doesn't happen immediately, though, because the neutrinos trapped in this nuclear matter heat it, temporarily stabilizing it from further collapse. "Only when the neutrinos all leave," says Brown, "does the star cool down"—and, if the core weighs more than 1.5 solar masses, collapse further into a black hole. If the core weighs less than 1.5 solar masses, it will remain what Bethe and Brown call a nucleon star, made of both protons and neutrons, rather than a neutron star.

How Brown and Bethe's revisionist view of supernovas will be accepted remains to be seen. Woosley thinks "we could still live in a universe with a maximum mass of a neutron star at 1.8 or even 2 solar masses, and not be in contradiction with anything we know." Adds Weaver, "There's a fair amount of uncertainty in the physics of the core collapse process. [The] idea is a good one, but it's premature to say it solves the problem."

Still, there may be a way to test the theory, says Kulkarni of Caltech. The places to look, he says, are globular clusters, the tight knots of old stars that form a halo around the galaxy and dot its disk. Over their long lifespans, globular clusters have experienced a lot of supernovas, and if Brown and Bethe are right, they should be rich in small black holes. In the crowded environment of a globular cluster, the black holes would tend to pair up with ordinary stars, forming binary systems that might be revealed by rare, powerful x-ray outbursts, caused when material from the companion star falls into the black hole.

Watching for these outbursts isn't a perfect test, though. One catch is that their violent birth process might have left many of the black holes traveling fast enough to fly out of the globular clusters before they paired up. Another is that the x-rays from a black hole binary may look a lot like those from a neutron star binary. Concludes Kulkarni, "It will take a while to say anything."

Bethe isn't worried. For now, he says, the scenario will stand or fall not on observational tests but on the plausibility of its picture of collapsing nuclear matter. When asked whether other astrophysicists will come around, he said, "Yes. Maybe not all, but many."

–Gary Taubes

SOLID-STATE PHYSICS

Artificial Atom Unveils Quantum Effects

Imagine you could attach electrodes to a single atom and directly measure its behavior as you add electrons or slowly vary a magnetic field. It sounds far-fetched, but in the last several years, physicists have learned to do something like that. The physicists' toolbox isn't quite up to managing that trick with real atoms, though. Instead, they work with "artificial atoms": tiny patches of metal or semiconductor in which electrons are so tightly confined by electric fields that they fall into the kind of quantum energy levels seen in a real atom. But so far, physicists have had trouble making meaningful measurements on artificial atoms holding fewer than 100 electrons.

In last week's *Physical Review Letters*, Massachusetts Institute of Technology (MIT) physicist Ray Ashoori announced a new artificial atom, developed while he was a postdoc at AT&T Bell Laboratories, in which he can study as few as one or two electrons. "[Other physicists made] artificial uranium—we're making artificial hydrogen and helium," says Ashoori. "It's a much simpler thing to think about." With it, he can map out the atom-like energy levels with unprecedented resolution and study interactions among small numbers of electrons—phenomena that could become critical as technology starts to incorporate devices this tiny. "We all believe that these small semiconducting devices will be at the heart of computers," says physicist Ned Wingreen of the NEC Research Labs.

Ashoori makes his version of an artificial atom—also known as a quantum dot—in a thin layer of the semiconducting material gallium arsenide sandwiched between two layers of insulating material. Electrodes go on the top and bottom. When he applies a tiny voltage, electrons in the bottom electrode "tunnel" through the insulating layer into the gallium arsenide. Ashoori configures the top electrode so that it generates an electric field, drawing the electrons into a patch of gallium arsenide only a few hundred angstroms across. That region is still several hundred times the size of an atom, and each electron's quantum "wave function" spans many real atoms in the semiconductor. But the confinement area is still small enough to give rise to large quantum mechanical effects, mirroring what happens in a real atom.

Monitoring the electrons isn't easy, though. Ashoori relies on the fact that the movement of an electron from the bottom electrode into the dot creates a tiny, fraction-of-an-electron change in the charge of the upper electrode, which he measures using an ultra-sensitive transistor known as a HEMT—a High Electron Mobility Transistor, which amplifies a small change in input to a large voltage. MIT physicist Marc Kastner, who coined the term artificial atom, says he's impressed. "It's just awesome that anyone can measure single electrons," he says. "It's mind boggling."

That ability is opening the door to phenomena researchers have long wanted to observe in action, such as the effects of a magnetic field on the behavior of a pair of electrons in a confined region. In a larger area, the electrons would steer clear of each other, repelled by their identical negative charges. In the dot, however, they are forced to lie right on top of each other, like the electrons of a helium atom. However, a rule of quantum mechanics known as the Pauli exclusion principle prohibits two electrons in an atom from occupying the same quantum state at the same time, and these electrons generally distinguish themselves by a directional property known as spin.

An applied magnetic field tends to force the spins into alignment, which would make the electrons identical again. To conform to the Pauli rule, the electrons must find a new way to distinguish themselves, and so one jumps to a higher energy level. In an ordinary helium atom, forcing an electron to make the jump takes a magnetic field of hundreds of thousands of tesla—stronger than the magnetic field on the surface of the sun. In the artificial atom, theorists predicted just a year ago, it should it take just a few tesla. Ashoori explains that the spacing between energy levels is much smaller in the artificial atom, and the repulsive force between electrons plays a much larger role. As a result, they are more prone to jump out of each other's way given a magnetic push. Ashoori has now been able to demonstrate this effect in his two-electron artificial atom.

There's much more to explore in the world of artificial atoms, says Ashoori. Among them are the interactions of three to 10 electrons, a range that Ashoori says is "the subject of theoretical speculation." He also hopes to build artificial atoms that would mimic the magnetism of real iron. Beyond that, he envisions artificial molecules, formed by putting two artificial atoms in close enough proximity to form artificial chemical bonds. He might start with a hydrogen molecule, he says, and move on from there.

–Faye Flam