ASTROPHYSICS

A Towering Physicist's Legacy Faces a Threatening Future

On the centennial of Hans Bethe's birth, his successors worry that cuts in long-planned projects will discourage the next generation of brilliant minds

ITHACA, NEW YORK—The language of astrophysics sizzles with alpha particles and gamma rays. There's a heavy dose of beta as well—Hans Bethe, that is, a giant of 20th century science, whose prowess in nuclear physics led to his fascination with combustion in deep space.

Bethe probed astrophysics at its purest levels right up until his death last year at age 98 (*Science*, 8 April 2005, p. 219). At a recent meeting* here, speakers fondly recalled his influence in the region where nuclear physics and astrophysics fuse, from neutrinos to supernovae, and ordinary stars to neutron stars. They also laid out key mysteries that still tantalize scientists: How do giant stars explode and forge the elements around us? What happens when neutron stars or black holes crash? And what is the nature of the dark matter and dark energy that suffuse space?

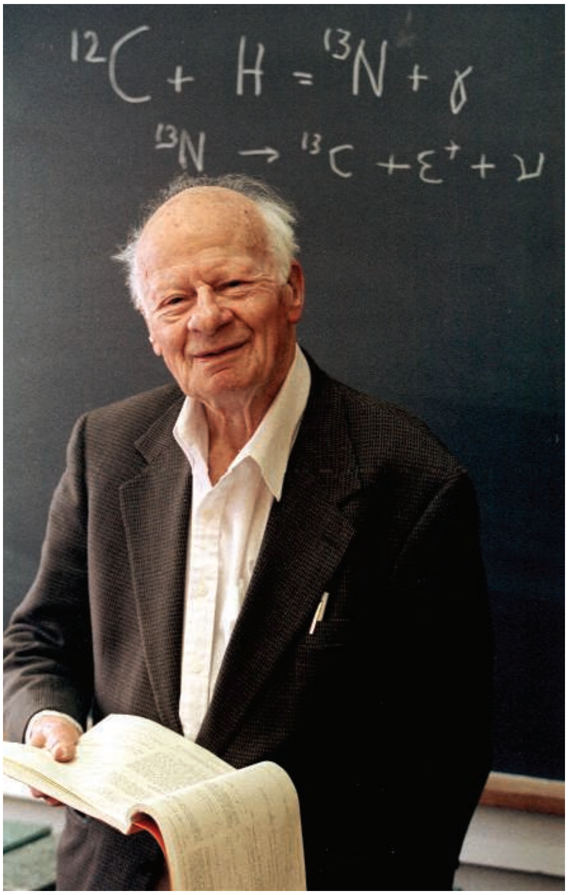
But as Bethe's scientific descendents marked what would have been his 100th birthday on 2 July, they worry about their ability to address such questions anytime soon. Cuts in the science program at NASA have cast a pall over missions designed to turn the cosmos into a high-precision physics laboratory. The damage to Bethe's legacy could be serious, they warn.

"In the worst-case scenario, the young people we need may feel hopelessness," says Saul Teukolsky, chair of the physics department at Cornell University—Bethe's academic home for 70 years. "They may not enter the field at all."

Bomb physics, near and far

Astrophysics was the alpha and omega of Bethe's long career. Although his fame stems from leading the theoretical division at Los Alamos, New Mexico, during the Manhattan Project, and his tireless advocacy of arms control once World War II was over, astronomers and physicists revere him as "the guy who figured out how the sun works," says astrophysicist Michael Turner of the University of Chicago, Illinois. "You don't need a better legacy than that."

Born in Strasbourg, Germany, and educated at universities in Frankfurt and Munich, the young Bethe spelled out the details of the proton-proton reaction that propels hydrogen fusion in the cores of modest stars like our sun. In the late 1930s, he was the first to describe a separate fusion cycle involving carbon, nitrogen, and oxygen atoms, which powers massive stars during their short lives. In 1967, Bethe received the Nobel Prize in physics for that work.



A rare spark. Hans Bethe, shown at age 90, calculated how stars burn—including the "carbon cycle" in background.

In the decades after World War II, Bethe's research focused on the theory of nuclear matter and atomic physics. A highlight was a calculation of a subtle shift in the energy levels of electrons in excited hydrogen atoms. That three-page paper, written on the train between New York City and Ithaca, set the stage for modern quantum electrodynamics.

Later in life, however, two catalysts drew Bethe tirelessly back into astrophysics. The 1967 discovery of pulsars—flashing deep-space beacons that Bethe's Cornell colleague Thomas Gold explained as spinning neutron stars—sparked Bethe's intense desire to understand the properties of superdense states of matter. Drawing from his deep well of nuclear physics, Bethe and colleagues wrote papers on the internal structures of neutron stars. They derived a likely radius of 10 kilometers, a figure still in vogue.

Soon after Bethe "retired" in 1976, his friend Gerald Brown of the State University of New York, Stony Brook, piqued his interest with a challenge to work out the nature of supernovae. The two scientists spent much of the next 3 decades pondering how giant stars blow up, their prodigious outbursts of neutrinos, and binary systems of neutron stars and black holes.

These topics followed logically from Bethe's work on the atom bomb, says astrophysicist Stan Woosley of the University of California, Santa Cruz. "Stars are gravitationally confined thermonuclear reactors," and their demise is bomb physics on the grandest scale, Woosley says. "And Hans was really interested in the birth of the elements, especially uranium," he adds with a smile.

Bethe wanted to find the essence of why a dying star's core implodes. His key contribution, says Woosley, was to consider the star's entropy. As a star runs out of fuel and fuses heavier elements up to iron, Bethe found, the outer layers grow disordered while entropy declines at the blazing core. "Hans liked to say [the core] had the entropy of an ice cube, even though it was 10 million times hotter than hell," Woosley recalls. Bethe calculated that when the core collapses, it has too little entropy for iron nuclei to break up. Instead, they compress into the extraordinary densities of neutron stars.

That collapse ignites an outward shock wave, which the great mass of the star quickly snuffs out. Bethe believed neutrinos emitted by the newborn neutron star would relaunch the shock wave and drive the supernova blast, a scenario he published in his 80s with astrophysicist James Wilson of Lawrence Livermore National Laboratory in California. The verdict is still out; the best computer models have yet to blow up a simulated star in a convincing way.

Solar neutrinos also captivated Bethe. With the late John Bahcall of the Institute for Advanced Study in Princeton, New Jersey, Bethe helped explain why underground detectors on Earth observed only a fraction of the

* Bethe Centennial Symposium on Astrophysics, Cornell University, 2–3 June.

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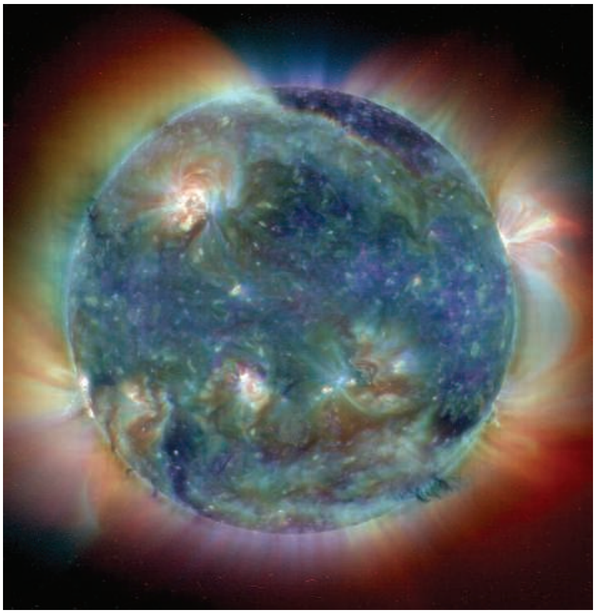

Ablaze with energy. Neutrinos from our sun drew Bethe's focus late in his career.

neutrinos predicted to stream from the sun's core. Confirmation came from Canada's Sudbury Neutrino Observatory in 2001: The particles have minuscule masses and oscillate among different "flavors." That behavior, as Bethe and Bahcall foresaw a decade earlier, arises from unknown physics beyond today's standard theory.

Neutrinos are so elusive that physicists still have no direct evidence of Bethe's carbon-nitrogen-oxygen cycle. That fusion should happen in our sun, albeit more sedately than in massive stars. "He would want us to verify that," says physicist Wick Haxton of the University of Washington, Seattle. Doing so, however, will require sensitive new experiments—such as a proposal to place a 130-ton vat of liquid neon at Sudbury to spot low-energy neutrinos.

Bethe also did not live to see a test of a claim that he, Gerald Brown, and Chang-Hwan Lee of Pusan National University in Busan, Korea, made—after Bethe turned 90—that binary systems containing two black holes should be 20 times as abundant as systems with one black hole and one neutron star. Their prevalence would be good news for the Laser Interferometer Gravitational-Wave Observatory (LIGO), which seeks the space-rippling disturbances caused by the mergers of such binaries. Two black holes should make a more violent "splash" in the gravitational pond of space, says theorist Kip Thorne of the California Institute of Technology (Caltech) in Pasadena, who motivated Bethe to probe the issue.

An endangered generation

The Laser Interferometer Space Antenna, long under development with the European Space Agency as a sensitive partner to LIGO, is one of three major space science missions planned by the astrophysics community in the next decade to peer further into Bethe's realm. The other projects are the four telescopes of Constellation-X, a high-resolution successor to the Chandra X-ray Observatory; and NASA's share of the Joint Dark Energy Mission, an effort with the U.S. Department of Energy to chart the weird speeding-up of the universe's growth and determine its cause.

But funding prospects are dim (*Science*, 17 March, p. 1540). A tight NASA budget, combined with massive cost overruns and a huge backlog of proposed projects, has left them competing for what could be only one new NASA start for a major astrophysics mission in the next 3 years.

The pain spreads to NASA's low-cost Explorers, which many view as the field's soul. Often led by universities, these missions draw students and yield outsized scientific results, says astrophysicist Roger Blandford, director of the Kavli Institute for Particle Astrophysics and Cosmology at Stanford University in Palo Alto, California. "You optimize the use of finite resources most efficiently by putting them into Explorer programs," Blandford says. "Instead, NASA has been starving them to death," including cancellation in February of the on-budget NuSTAR mission to image high-energy x-rays.

Where next? In the post-Bethe era, astrophysicists face tough choices—and a hard act to follow.

Some researchers at the meeting pinned these sacrifices on NASA's decision, after much political intervention, to fund a repair mission for the Hubble Space Telescope and to push ahead with its planned successor, the costly James Webb Space Telescope (JWST). "We could just see [Hubble] would be a $2 billion drag on the program," says Turner, who recently completed a 3-year stint as head of mathematical and physical sciences at the National Science Foundation. Given all of NASA's other priorities, Turner says, moving forward with the repair without reconsidering its value within the entire suite of missions "was stupidity on stilts."

But other scientists believe that prolonging Hubble's life didn't automatically take money away from other programs because space science isn't a zero-sum game. Even with no servicing mission, "it's not clear that money would be made available for Explorers, or Constellation-X, or anything," says astronomer Robert Kirshner of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts. He also notes that Bahcall led a National Academies' committee that in 2003 came out strongly in favor of at least one more NASA repair flight to the telescope, after extensive community input.

More vexing for the long-term health of astrophysics is the ballooning cost of JWST, now pegged at $4.5 billion. "I worry that we've gotten ourselves into the SSC [Superconducting Super Collider] mentality, that we need $5 billion to do what's next, and everything else can go to hell," says astrophysicist David Helfand of Columbia University. "We may suffer the same fate our particle-physics colleagues did 15 years ago," he adds, referring to Congress's decision in 1993 to cancel the partially built accelerator in Texas. Astrophysicist Shri Kulkarni of Caltech paints the situation bluntly: "Is a single mission worth the rest of astronomy?"

No one at the meeting had a good answer, and there was no consensus on how the community might gain the necessary political support for its priorities. Indeed, the room seemed infused with a wistfulness that Bethe couldn't be there to rally his colleagues in their time of need. "The scope of problems he could solve pretty much had no limit," Brown wrote last year in *Physics Today*, recalling his struggle to keep up with a friend 20 years his senior. "In that sense, I think [Bethe] was the most powerful scientist of the 20th century."

–ROBERT IRION

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