News Flash: Astronomers Demystify Gamma-Ray Bursts

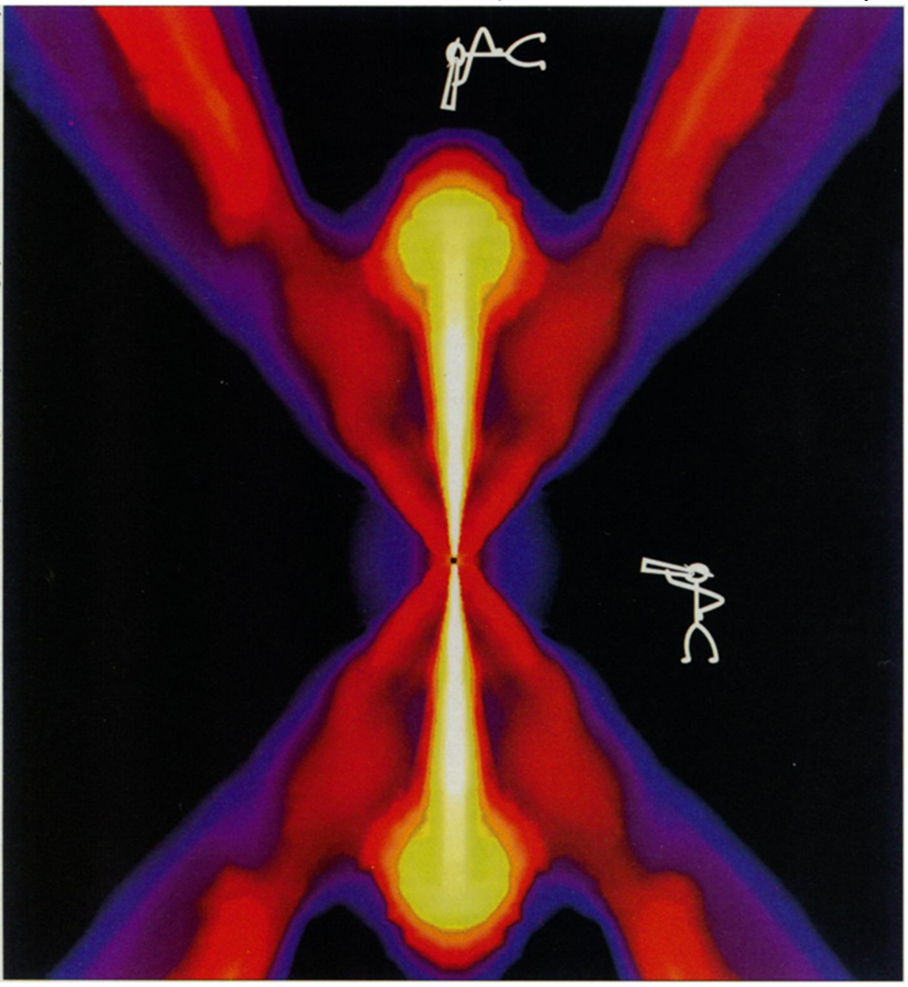
Brightest lights may herald the birth of black holes

By RON COWEN

For a few brief shining moments, a gamma-ray burst radiates more light than anything else in the universe does. Then the light vanishes, never to be seen again.

For 3 decades, astronomers have puzzled over the nature of these fleeting powerhouses. A growing body of evidence now suggests that the brightest events in the cosmos signify the birth of its very darkest inhabitants. Gamma-ray bursts may herald the formation of the dense, collapsed stars known as black holes.

"After 30 years, the mystery of gamma-ray bursts has been partially resolved," says Tsvi Piran of Hebrew University in Jerusalem and New York University. He described recent progress at a cosmology meeting last May at the Fermi National Accelerator Laboratory in Batavia, Ill.



Color simulation by Woosley, McFadyen; Drawing by Tim Jones/McDonald Observatory

This simulation begins with a doomed, massive star that has shed its hydrogen envelope. The black hole formed by the collapse of this heavyweight generates tightly focused jets that expand freely into space. The jets maintain their energy source—material falling onto the black hole—long enough to produce a 20-second gamma-ray burst. Drawing illustrates that an observer (top) along the line of fire of a jet would see the burst, but someone in a different location (right) would not. Theorists conjecture that the rate at which bursts are generated could be 100 times greater than the rate astronomers have deduced from the number detected in Earth's vicinity.

A supermassive black hole—the remains of millions to billions of stars at the center of a galaxy—can produce an extensive assortment of fireworks. Astronomers similarly suspect that stellar black holes—bodies formed from a single star—may produce a wide assortment of gamma-ray bursts lasting from one-hundredth of a second to several minutes.

Material falling onto a stellar black hole accelerates rapidly and releases a huge amount of energy. According to models that astronomers have been tinkering with for years, such energy is more than enough to power a gamma-ray burst. Recent observations have made such theories more compelling.

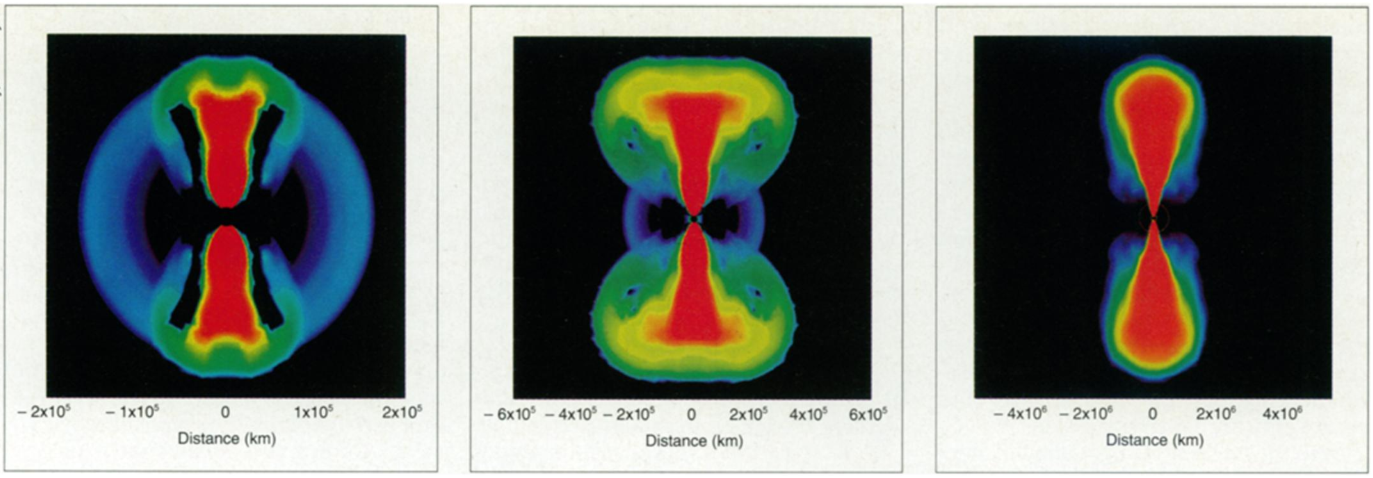
It takes a massive star to make a stellar black hole. Over the past 2 years, astronomers have seen several gamma-ray bursts in places where such behemoths, several times the mass of the sun, are likely to be common.

Massive stars never stray far from their birthplace during their brief lives and typically die a catastrophic death. By pinpointing the location of the long-lived bursts—those that last 5 seconds or more—the X-ray satellite BeppoSAX has for the first time enabled other telescopes to home in on the embers of these fiery flashes.

Lasting from hours to days, these afterglows reveal that the bursts come from distant galaxies, many of them with the bluish tinge and dusty appearance typical of regions that churn out young stars, including massive ones, at an enormous rate.

In just a few million years, a massive star exhausts its nuclear fuel, losing the fight against its own gravity. If the star ranges in mass between 8 and 30 times that of the sun, gravity abruptly crunches its core into a dense cinder known as a neutron star. At the same time, a

Woosley, McFadyen



The delayed demise of a star 25 times as massive as the sun leads to the formation of jets and possibly a gamma-ray burst. After gravity has collapsed the massive star's iron core into a neutron star, the dense object launches a supernova shock wave that isn't powerful enough to explode the star. Instead, material rains down on the core, which becomes a black hole. Some of the energy liberated by the infall of material is converted into highly focused jets (red regions). Ten seconds after the jets form (left), they begin breaking through the overlying material and overtake the supernova shock wave (the spherical region shown in blue). Seventeen seconds later (middle), the jets have reached well beyond the shock wave to the edge of the star's helium core. After another 41 seconds (right), the jets have penetrated the star's outer envelope of hydrogen and are on their way to exploding the star.

shock wave hurls the dying star's outer layers into space. Astronomers call that explosion a supernova.

Extremely massive stars, however, lack the oomph to launch a supernova shock wave. There's simply too much matter falling onto the core to allow the wave to form. Instead, gravity continues crushing the condensed core until not even light can escape its grasp. A black hole is born.

In a model developed by Stan Woosley of the University of California, Santa Cruz and his colleagues, this failed supernova, or collapsar, produces a gamma-ray burst that lasts about 20 seconds.

Woosley begins with a doomed star, 35 times as massive as the sun, that loses its outer envelope of hydrogen gas. The envelope, about two-thirds of the star's original mass, may be blown off by fierce winds from the star itself or snared by the gravity of a nearby companion.

According to the model, gravity promptly collapses the core to a rapidly spinning black hole, and overlying material begins to rain down upon it. Because the star had been rotating, the infalling gasses do not crash directly onto the hole but form a disk around its equator.

Within this superhot, highly magnetized disk of gas, nuclear reactions generate a rush of subatomic particles called neutrinos. In a matter of seconds, some of the energy either stored in the disk's magnetic field or carried by the neutrinos creates jets of electrons, neutrons, and protons that shoot out from the poles. Over the next 10 seconds, the jets, which carry as much energy as would be radiated by a billion billion suns, burrow through the remains of the star and blow it apart.

Having failed to generate an ordinary supernova, this sequence of events now produces an explosion with more than 10 times the punch. This souped-up version of a supernova is what Woosley and Bohdan Paczynski of Princeton University variously call a collapsar or hypernova.

Each jet breaks free of the surface and travels at nearly the speed of light for a distance comparable to 100 times the length of the solar system. At this point in their journey, the jets encounter interstellar material. As clumps of electrons in a jet collide with each other or slam into the material, they emit a high-energy flash of radiation—the gamma-ray burst.

Piran, a theoretical astronomer, has been independently studying gamma-ray bursts. Although he subscribes to the outlines of Woosley's scenario, he suggests that the burst comes entirely from collisions between clumps of particles within each jet.

Piran and Woosley agree that the visible-light afterglow results from collisions between a jet and interstellar material that occur farther down the road, after the jet has spread out and slowed.

The gamma-ray bursts described by the model last for about 20 seconds, says Woosley. Some bursts, however, last for several minutes. For these longer flashes, Woosley and Andrew MacFadyen, also of Santa Cruz, invoke a variation on the black-hole theme. Woosley described the work at a May workshop on gamma-ray bursts and supernovas at the Space Telescope Science Institute in Baltimore.

It's another case in which failure leads to success.

In their latest simulations, Woosley and MacFadyen begin with another heavyweight, a star about 25 times as massive as the sun, that has also lost its outer envelope. At the end of this heavyweight's life, its core collapses to become a neutron star, and an outgoing shock wave plows into the outer layers of the star.

For this star, however, the supernova shock is a tad too wimpy. It lacks the punch to blow the entire star to smithereens. Instead of completely exploding, after about 200 seconds some of the material, the equivalent of five suns, comes crashing down on the core. Material shot out farthest by the supernova shock takes several minutes to fall back.

The weight quickly becomes more than the neutron star can bear, and it turns into a black hole. As before, the infalling gas forms a disk around the newly minted black hole. This time, however, the matter spirals more gradually into the hole—and the energy from the neutrinos is not enough to make jets.

Instead, says Woosley, magnetic fields associated with the disk may do the trick. Wound up by the spinning black hole, the magnetic field snaps like a rubber band. Some fraction of that torrent of energy generates the jet, Woosley proposes.

Because the matter continues to fall onto the black hole for several minutes, this process "creates a powerful jet that can stay on for a long time—hundreds of seconds," he says.

Overtaking the shock wave from the supernova, the jets spread out and send their own shock waves hurtling through the star's outer layers, ensuring that the star will explode. These longer-lasting jets may account for gamma-ray bursts that sustain their fireworks for several minutes, Woosley says.

Such models may seem contrived, but recent observations have boosted their credibility. For nearly a year, a group of astronomers from the California Institute of Technology in Pasadena studied the region of the sky where BeppoSAX detected a gamma-ray burst on March 26, 1998. After 3 weeks, the visible-light afterglow had faded, and Joshua S. Bloom and his colleagues figured that the faint light remaining was background light from the burst's home galaxy. But when they looked again 9 months later, the light was gone.

A galaxy cannot simply wink out of existence, but a supernova can. Bloom and his colleagues propose that the light they saw had been coming from a supernova, which only became visible after the burst's glowing embers had died.

Both the color of the light and its intensity several months after the burst suggest that the supernova—and the gamma-ray burst—came from a galaxy about 7 billion light-years from Earth. Unlike gamma-ray bursts, supernovas much farther away aren't bright enough to be seen. This could explain why astronomers have been able to link a supernova or hypernova explosion with only a few of the bursts they have observed.

To explain the connection between another supernova, dubbed 1998bw, and a gamma-ray burst detected on April 25, 1998, Woosley invokes yet another variation of the black hole–hypernova model. In this case, the jet is either poorly focused or loses most of its energy in exploding the star it travels through. Consequently, the gamma-ray burst it produces is an unusually weak one.

This could explain why the April 25 burst was considerably fainter than several of the other gamma-ray bursts that telescopes have recorded. Astronomers caution, however, that although supernova 1998bw lies within the same general region as the burst and exploded about the same time, its position may not be identical to that of the burst.

With all this talk of jets comes an intriguing possibility. Each day, NASA's Compton Gamma Ray Observatory detects, on average, one gamma-ray burst. If the bursts are in fact produced by highly focused jets, we may be seeing only those shot toward Earth.

"We only see a burst when we're looking straight down the jet," says Woosley. "A lot of gamma-ray bursts go unobserved because the gun isn't pointed at us." The actual rate at which bursts occur could be 100 times higher, he calculates.

By the same token, if astronomers are seeing focused gamma rays, then each burst would have much less total energy than is often estimated. In the past, they have assumed that a gamma-ray burst radiates energy equally in all directions and that the amount recorded near Earth represents but a tiny fraction of the total energy.

If the new models are correct, afterglows should be visible much more often than the bursts themselves. That's because the jets widen as they slow down and create the afterglow. Indeed, says Piran, finding "orphan afterglows"—fading optical and radio-wavelength embers with no obvious parent gamma-ray burst in sight—would help to verify that jets play the key role that astronomers suggest.

Not everyone is enamored with the models. Although Paczynski invented one version of the hypernova theory, he says he's not convinced that it or any other burst model is the right one.

Finding and studying afterglows "was a real breakthrough, but I don't take seriously any of the models of the gamma-ray bursts themselves," he says. "I don't want to argue about the details because really we don't understand [the theories]."

Bloom's work linking a supernova to a gamma-ray burst is "likely to be correct," says Paczynski, but with only a handful of observations, "we don't have a pattern yet."

Piran takes a more optimistic view. "It's very easy to say we don't know," he says, "but we've come a long way."

Paczynski and Piran agree that a deeper understanding of gamma-ray bursts is on the horizon. Early next year, NASA will launch a spacecraft that promises to locate the position of gamma-ray bursts—both long and short ones—to unprecedented accuracy. It comes equipped with an X-ray telescope to pinpoint the bursts with 50 times the accuracy of BeppoSAX.

Moreover, the craft, known as the High Energy Transient Experiment-2 (HETE-2), will relay that information to ground-based telescopes within seconds, so they can focus on the bursts before they vanish.

Several theorists have proposed that the very short bursts, those that last less than a few seconds, involve pairs of massive stars. Woosley notes that it's difficult for a black hole formed by the collapse of a single star to generate such short bursts. Instead, pairs of neutron stars that merge and make a black hole could generate these flashes. Such pairs tend to have migrated away from star-forming regions.

With HETE-2, "we shall see the host galaxies [of bursts] in much more detail," says Paczynski, and then determine whether the bursts observed are actually in the star-forming regions.

"The diversity of bursts from all over the sky will enormously improve the statistics of the afterglow, and you will catch more optical flashes early on," he says. "I cannot tell ahead of time what we will learn from that, but certainly it will provide many, many hints about what is going on." □