Anatomy of a Supernova

A shocking story: Hubble and ROSAT view the Cygnus Loop

By RON COWEN

When a massive star runs out of fuel and can no longer resist the pull of gravity, its core rapidly shrinks to a tiny fraction of its original size. But like a spring wound too tightly, the collapse triggers a rebounding shock wave that hurls the star's outermost layers of gas into space. This explosion, called a supernova, is the swan song signaling the star's demise.

But a supernova serves as more than a harbinger of death. It also sows the seeds of a new generation of stars.

Carbon, nitrogen, oxygen, sulfur, and other elements produced inside stars come spewing out of the supernova and mix with the interstellar medium. But the blast carries with it more than just the innards of the star that was. Neutrons produced in the outburst bombard these atoms, forging nickel, copper, zinc, iron, and even heavier elements – materials that not even the hottest stellar furnace can make. And as the shock wave of the supernova races ever farther from its parent star, it sweeps away any surrounding gas. All this stuff gets pushed, stirred, plowed, and piled into regions of space tens to hundreds of light-years from the explosion. Thus, supernova remnants seed the cosmos with the raw materials from which people, planets, and this printed page are made.

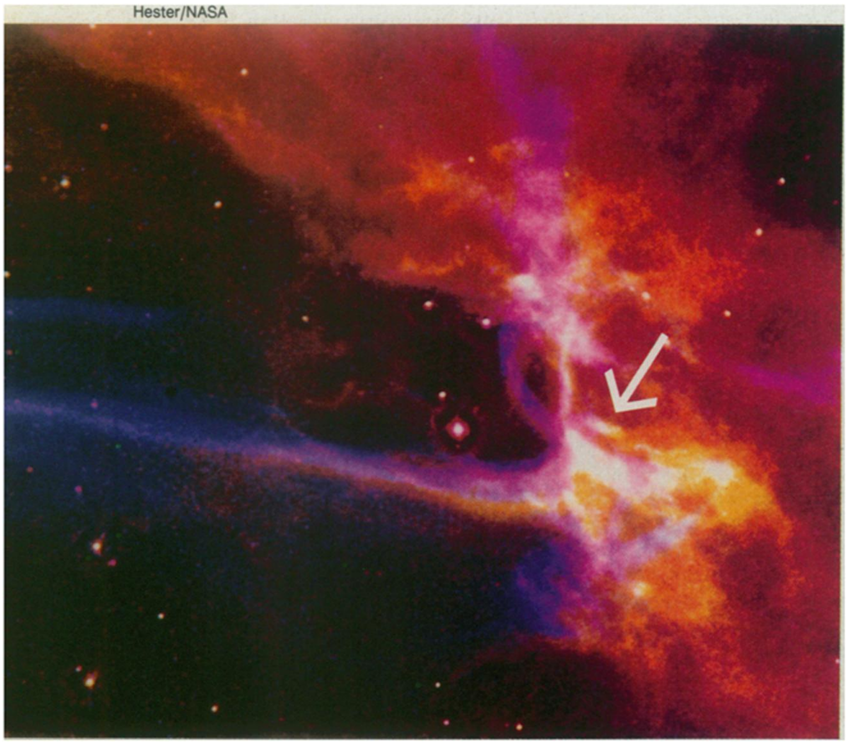
Little wonder, then, that modern astronomers find supernovas as fascinating as ancient stargazers found the birth of these exploded stars. Supernovas reveal much about the chemical composition of the cosmos, as well as the nature of interstellar space, says J. Jeff Hester of Arizona State University in Tempe.

And among the remnants of these explosions, the Cygnus Loop – a broken, brightly lit ring measuring 137 light-years across – stands out as a prime target for observers. This spherical shell looms six times larger (though far fainter) on the sky than the full moon and is one of the nearest supernova remnants to Earth. Moreover, it lies in one of the least dust-obscured regions of our galaxy.

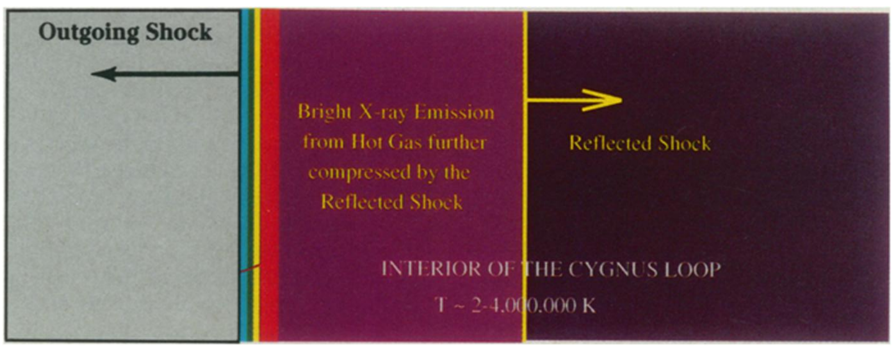
In April 1991, a camera aboard the Hubble Space Telescope cast its eye on a tiny portion of the eastern edge of the Cygnus Loop. In homing in on a mere 0.7 percent of the remnant, the telescope captured the anatomy of the region just behind the speeding shock wave in 10 times greater detail than ever before. Hubble brought features of the explosion into sharp focus, resolving regions as small as the width of the solar system. Hester and his colleagues presented the images in January at a meeting of the American Astronomical Society in Phoenix.

Supernova shock waves heat the normally invisible interstellar medium, cooking it until it glows at visible-light temperatures of up to several hundred thousand kelvins. The Hubble images reveal that immediately behind the shock wave lies a hotter

Hester/NASA



Hubble image shows false-color view of the eastern edge of the Cygnus Loop supernova remnant. Arrow indicates what appears to be a bullet of gas that only recently emerged from the remnant's interior and caught up with the main shock wave. Blue denotes the hottest emissions, red the coolest.



Hester

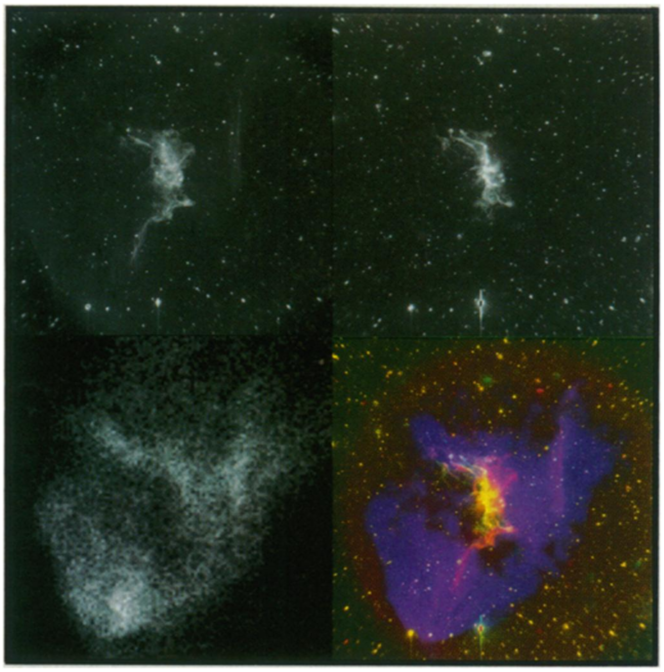
Anatomy of a supernova shock wave: Outgoing wave collides with dense clouds, slowing down and sending a reflected wave back in the opposite direction. Material directly behind the outgoing shock wave cools by emitting visible light, with warmest emissions (blue) closest to the wave front. Hotter gas, caught between the outgoing and reflected waves, emits bright X-rays.

region trailed by a cooler one — with a clear separation between the two. Presumably, the trailing region has a lower temperature because it has emitted more visible light, radiating away more of the kinetic energy it gained when the shock wave plowed through it. While astronomers had previously suspected such a temperature structure might exist, visible-light images from the ground could not discern it, because Earth's turbulent atmosphere blurs the boundary between the hotter and colder regions.

"We are now close enough to the shock wave to see the bones and sinews of it," Hester says.

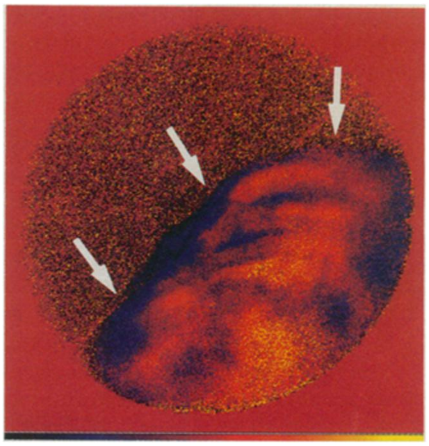
The new work, in combination with X-ray views of other parts of the Cygnus Loop obtained with ROSAT, a German-U.S.-British X-ray observatory, marks a turning point in our understanding of the evolution of supernova remnants, says astronomer Ryszard Pisarski of NASA's Goddard Space Flight Center in Greenbelt, Md. Along with ground-based observations, Hester adds, these studies enable researchers to compare directly for the first time the structure of an actual supernova shock wave to theoretical models.

Such models help describe other violent phenomena in astrophysics. These include the fierce winds from newborn stars, the explosive brightening of stars known as cataclysmic variables, and the interaction between gas and high-speed jets of particles and radiation in active galaxies.



Palomar Observatory, ROSAT

Images show the same Cygnus Loop region illuminated by visible light from hydrogen atoms (upper left), visible light from oxygen (upper right), and X-ray emissions (bottom left). Color image combines these views, with yellow denoting a mix of oxygen and hydrogen emissions, pink denoting a mix of oxygen and X-ray emissions, and purple denoting X-rays.



Cioffi, Pisarski

In this false-color view of a portion of the Cygnus Loop, speckled emission at upper left is background radiation. Temperature is cooler at the rim of the remnant (blue area indicated by arrows) and warmer toward the center (yellowish area at lower right corner).

In recording visible-light emissions from three types of atoms that glow at different temperatures, Hubble's wide-field/planetary camera acted as a thermometer, measuring the temperature variation in the recently shocked gas. Within a relatively small region behind the expanding shock wave — measuring just a few hundredths of a light-year across — the hottest emissions lie nearest the shock wave and come from ionized oxygen. Radiation from ionized hydrogen follows just in back of the oxygen glow. The coolest visible-light emissions measured come from ionized sulfur, which resides farthest behind the shock wave.

Collaborating with James Graham of the University of California, Berkeley, Hester has also compared ground-based, visible-light images of the southeastern part of the Cygnus Loop with close-up X-ray pictures of the same region recently taken by ROSAT. The astronomers have found that X-ray radiation — associated with temperatures 100 times hotter than those of atoms emitting visible light — concentrates in an area directly behind the cooler optical emissions.

A more panoramic X-ray view of the Cygnus Loop, taken by ROSAT and analyzed by Pisarski and Denis F. Cioffi at NASA headquarters in Washington, D.C., also shows that X-ray emission is most intense behind the visible-light radiation.

But what makes the gas there hot enough — several million kelvins — to generate X-rays? Hester and other researchers suggest that the gas is squeezed between two shock waves: the initial, outgoing wave and a reflected, backward-moving shock wave generated when the original blast slams into dense gas clouds. The situation, he notes, is similar to what happens when an ocean wave hits a sandbar; some of the energy in the wave is reflected back toward the sea.

The reflected shock wave further compresses and heats up gas already jazzed by a violent encounter with the original, outgoing shock wave. The one-two punch from the outgoing and incoming shock waves leads to much brighter X-ray emission than the passage of the original wave alone.

Hester notes that the X-ray findings support a model of the optical appearance of the Cygnus Loop that he and Donald P. Cox of the University of Wisconsin-Madison proposed in 1986. This model accounts for the shape of the slender filaments of gas that glow in visible light near the edge of the Loop. Hester and Cox suggest that the glowing filaments are produced when the initial blast collides with large clouds of interstellar gas, compressing them into rippled sheets of glowing material. From Earth, some of the rippled sheets are viewed edge-on and thus appear as filaments.

Crashing the first shock wave into a large, dense cloud slows the wave — in this case, from an initial speed of about 400 kilometers per second to about 100. The temperature immediately behind the slowed-down shock wave is too low for X-rays to form. However, it is warm enough for the gas to glow in visible light. The net result is cool, visible-light emission just in back of the outgoing shock wave. Just behind the cool emission lies the X-ray emission, emitted by gas caught between the outgoing wave and the reflected shock, Hester says.

If the shock wave had instead encountered much smaller clouds embedded in the interstellar medium — as has often been assumed — the blast would have engulfed the clouds completely and broken them into fragments. As the tiny clouds heated and fragmented, they would have radiated X-rays. Because the small clouds take time to break apart, the X-ray emission would not lie just behind the shock wave. Instead, the radiation would be smeared across a much wider swath of the Cygnus Loop than has been observed, Hester says.

ROSAT observations analyzed by Pisarski and Cioffi appear to support the view that most X-ray emissions are triggered by the impact between shock waves and large gas clouds, Pisarksi says. The researchers found that within the zone of X-ray emission, radiation produced farther back from the optical emission – closer to the site of the supernova explosion – has a higher temperature. Collisions between shock waves and small gas clouds don't seem to account for the temperature difference, he says. In such a model, Pisarski notes, the shocked clouds would have fragmented and dispersed throughout the interstellar medium, resulting in a far more uniform temperature throughout the X-ray-emitting region.

Hester believes that although the supernova at the heart of the Cygnus Loop exploded some 15,000 years ago, the shock wave has only recently encountered dense, large gas clouds. In this scenario, the massive parent star that spawned the supernova had a substantial wind and emitted intense ultraviolet radiation. Over about 10 million years, both features of the parent star would have swept away much of the gas from the star's immediate vicinity, piling it into large outlying clouds. So when the star went supernova, the Cygnus Loop remnant expanded for thousands of years into a nearly gas-free cavity.

Now, according to Hester, the Loop has expanded to the edge of this local hole in space. There it encounters a different world. Smashing into giant gas clouds distributed relatively uniformly around it, the remnant lights up these denser regions of space. Such a model, Hester says, accounts for the juxtaposition of X-ray and visible-light emissions, as well as the smooth, generally spherical shape of the remnant.

While the Hubble images seem to have confirmed some existing models of supernova remnants, they are also revealing a wealth of surprises. One of the more striking – though speculative – findings is an apparent shaft, or bullet, of gas that has only recently emerged from the heart of the gas-free cavity. This Johnny-come-lately seems to have overtaken the shock wave, which has slowed considerably since moving farther from the site of the explosion. If the bullet model is correct and the shaft isn't simply an artifact of the image, then future Hubble photographs taken a year apart should show the material moving 2 to 3 arcseconds, about 0.03 light-years, across the sky.

In another part of the Loop, the Hubble photographs show several inverted V-shaped structures, with visible light emitted from the apex of the V. Hester suggests that such regions indicate where the shock wave has run into and wrapped around a small, dense clump of gas – much the way a rubber sheet might stretch if it wrapped around a bowling ball in its path. As the different parts of the shock wave join together on the other side of the clump, they exert a crushing pressure on the enclosed clump.

Intriguingly, the gas clumps seen by Hubble measure about the size of the solar system, and the pressure might be almost enough to trigger the formation of sun-like stars, Hester notes. Though he believes starbirth is unlikely in these small clouds, understanding the interaction between the shock wave and the clouds could improve understanding about shock-induced star formation, he says.

How much pressure is needed to trigger starbirth and over how much time? Must the shocked region have a minimum size in order to make stars? And what kinds of shocks are most likely to produce a family of stars similar in mass to the sun? As in other parts of the Cygnus Loop, conditions here seem ripe for answering questions that touch on fundamental astrophysics far beyond the expanding remnant. □