V1974 Cygni 1992: The Most Important Nova of the Century

by Sumner Starrfield and Steven N. Shore

Never has a nova been watched by so many astronomers with so many instruments. Since its discovery by Peter Collins, an amateur astronomer in Boulder, Colo., in the early morning of February 19, 1992, nova V1974 Cygni has been recorded in x-rays through radio waves and from the ground, the air, Earth orbit and beyond.

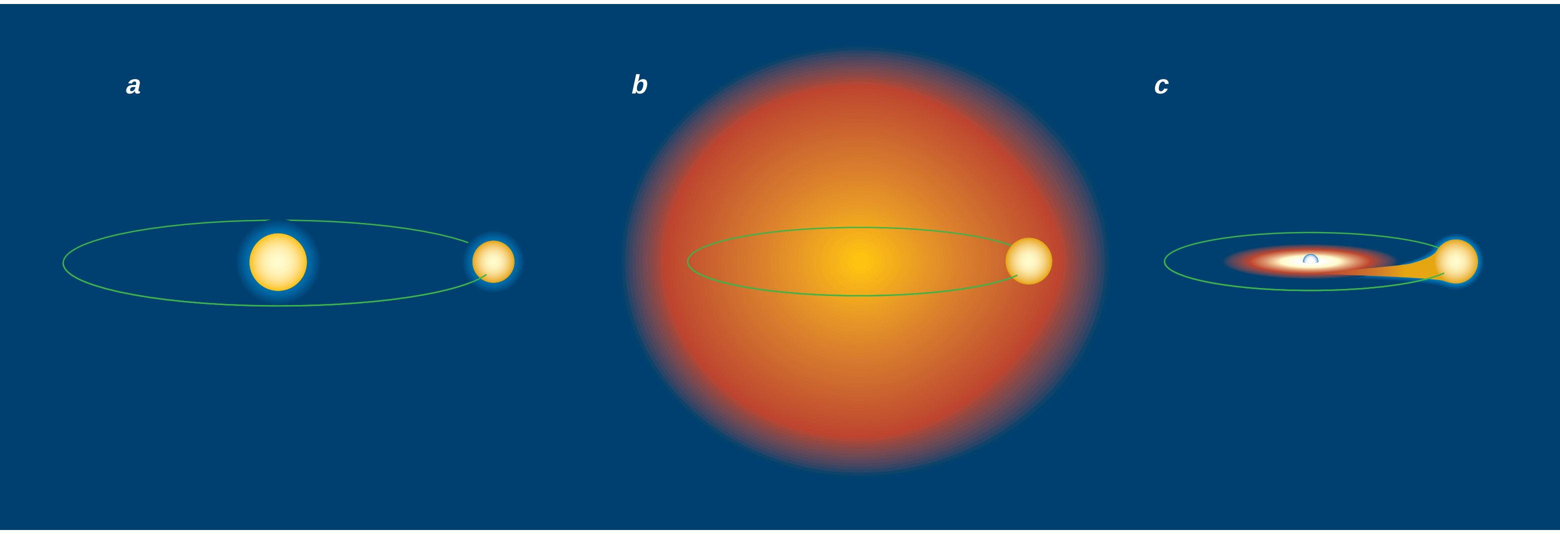
> This nova answered many questions during its life and raised more in death

Within hours of his report, we looked at the nova with the International Ultraviolet Explorer (IUE) satellite. We caught it in the "fireball" stage—familiar from photographs of hydrogen bomb explosions, when the gases are first expanding. Before long, it became the only nova to be seen both in birth and in death. In late 1993 the low-energy x-rays coming from the nova's core ceased, indicating to us that the nuclear explosion had run out of fuel.

V1974 Cygni 1992 confirmed many of our ideas about novae—such as how the ejected gases evolve—but also presented new challenges. It threw off about 10 times more matter than was expected, part of it in the form of dense knots and filaments. The knots may hold the key to the cause of the excess mass. They point to turbulent processes that dredged up material from the nova's core. Although we have been forced to rethink many details of how novae evolve, the most essential elements of the original picture remain intact.

In 1892 the nova T Aurigae became the first to be recognized as an explosion, from the peculiarities in its spectrum as compared with normal stars. Since then, scientists have found and studied one or two novae each year. A "naked eye" nova, such as V1974 Cygni, bright enough to be easily visible to the unaided eye, appears perhaps once in a decade.

About 40 years ago a picture of how novae occur began to



fall into place. In 1954 Merle F. Walker, then at the Mount Wilson and Palomar Observatories, discovered that the old nova DQ Herculis (which exploded in 1934) is a system of two orbiting stars. One of the stars in the binary system conveniently passes in front of the other, allowing astronomers to measure the time the two stars take to orbit each other. The period turns out to be extraordinarily short—four hours and 39 minutes. One star is also very small; we now know it to be a white dwarf.

White dwarfs, the end product of stellar evolution, have as much matter as the sun within a volume no larger than Earth's. Robert P. Kraft, also then at the Mount Wilson and Palomar Observatories, showed that other old novae are closely orbiting binary systems. In all these novae, one star was relatively large and unevolved, and the other was a white dwarf. But how can a white dwarf that has no remaining nuclear fuel, along with a stable companion star, give rise to an explosion 10,000 times brighter than the sun? It turns out that each star inexorably alters the other's development.

Calamitous Company

A nova system begins as a widely separated binary, in which one star is more massive than the other. The massive star evolves faster, fusing its hydrogen into helium through the "CNO" cycle of nuclear reactions, which involves carbon, nitrogen and oxygen. At the end of this stage the star becomes a red giant. Its surface swells, engulfing the smaller star. Meanwhile the more massive star fuses the helium in its core to carbon and oxygen.

The stars continue to orbit each other within the common gaseous envelope, losing orbital energy and angular momentum to the gas. As a result, gas is expelled from the system, and the two stars spiral in toward each other. Eventually all the material extending from the massive star past the smaller star is lost. At the end of this "common envelope" evolution, the distantly orbiting stars have become a close binary system. The massive star, having used up all its fuel, has transformed into a compact white dwarf. Its companion has remained relatively unchanged.

Suppose the stars are initially even more widely separated, and the more massive star began its life with about eight to 12 solar masses. Then the latter star can further fuse its core carbon into magnesium and neon. The white dwarf it ultimately becomes is made of these heavier elements, rather than just carbon and oxygen (a CO nova), and is called an ONeMg white dwarf.

Kraft also made the crucial discovery that the companion star is losing gas. After swirling around in an accretion disk, the hydrogen-rich gas falls onto the surface of the white dwarf. In 1972 one of us (Starrfield, then at the IBM Thomas J. Watson Research Center), along with Warren M. Sparks, then at the National Aeronautics and Space Administration Goddard Space Flight Center, James W. Truran, then at Yeshiva University, and G. Siegfried Kutter, then at the University of Virginia, developed computer simulations that showed how the accreted gas triggers the subsequent explosion.

The intense gravity on the white-dwarf surface compresses the gas as it falls in. If an amount of gas 100 times more massive than Earth accumulates on the white dwarf's surface, then the density in the bottom layer becomes more than 10,000 grams per cubic centimeter. (The density of water is one gram per cubic centimeter.) Because the gas is compressed, its temperature rises to a few million kelvins. The process of accumulation also mixes material from the core of the white dwarf into the overlying and infalling layers, thereby changing their composition.

Under these conditions, the hydrogen nuclei fuse into helium and release energy, by the same CNO nuclear reactions that power normal stars more massive than the sun. The material becomes even hotter, so that the fusion proceeds faster, creating runaway thermonuclear reactions like those in a hydrogen bomb.

If the gas were normal, then it would now expand and cool, thereby shutting off the fusion reactions. But the material on a white dwarf behaves in a peculiar manner described by quantum mechanics. It is packed together so tightly that the electrons, which are unable to interpenetrate, become the source

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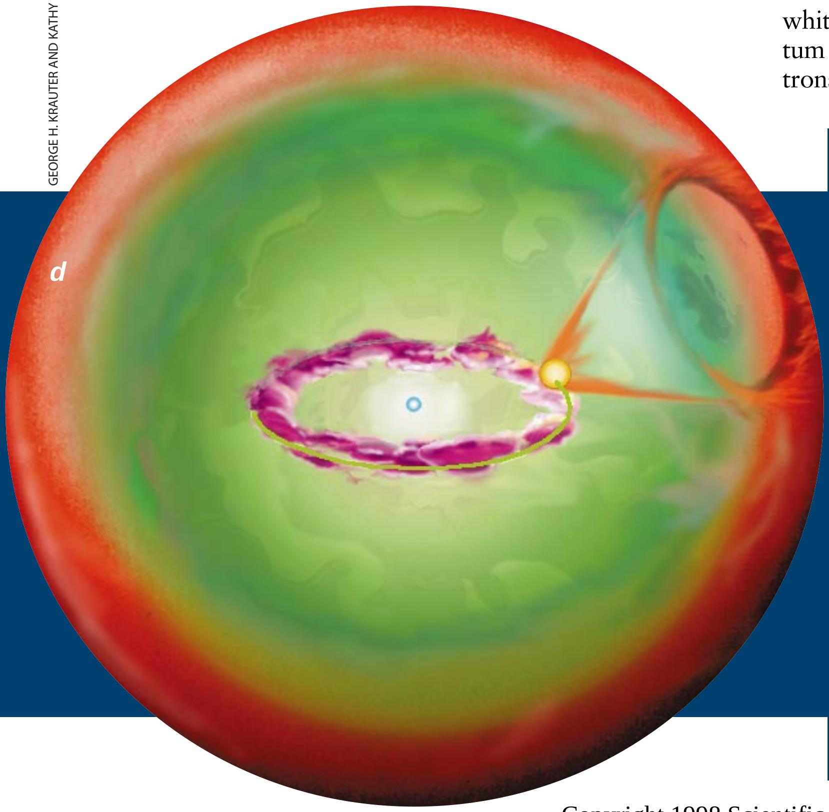
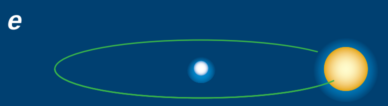
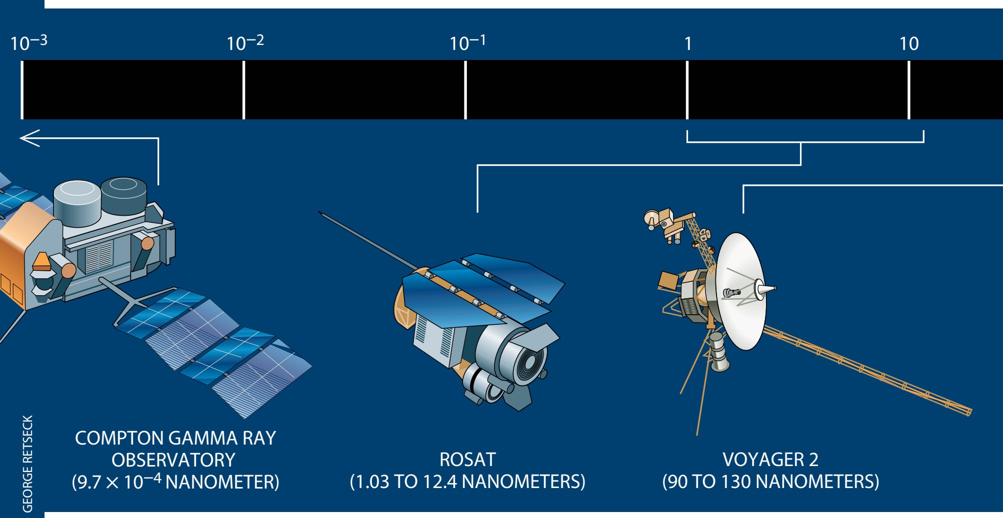




NOVA SYSTEM begins as a pair of widely separated orbiting stars (*a*). The more massive star evolves faster, becoming a red giant and enveloping the smaller star (*b*). The stars lose angular momentum to the gas and spiral in toward each other while the gas is expelled. Eventually they form a close binary system in which the remaining core of the red giant, having used up all its fuel, has become a white dwarf. The less massive star now sheds matter, which first forms an accretion disk (*c*). Falling onto the white dwarf's surface, this material is compressed by the high gravitational field. Then a runaway thermonuclear reaction—a nova explosion—takes place (*d*), stripping most of the accreted material off the white dwarf (*e*). It can, however, accrete fuel from its neighbor again, cycling through the steps from *c* to *e* many times.



DIVERSE INSTRUMENTS were used to study electromagnetic radiation of different wavelengths emitted by V1974 Cygni. The Compton Gamma Ray Observatory searched for photons emitted by the sodium isotope ^{22}Na (and found none). The ROSAT satellite detected x-rays coming from the burning core; the cessation of these rays signaled the nova's demise. Voyager 2, then beyond Neptune, observed far ultraviolet radiation, the first for a nova. The International Ultraviolet Explorer captured the explosion in its early fireball stage. The Hubble Space Telescope revealed clumps within the ejected gases. The 1.8-meter telescope at Lowell Observatory in Flagstaff, Ariz., recorded optical light, and the Very Large Array in Socorro, N.M., detected radio emissions that confirmed the presence of clumps.

of pressure. Unlike an ordinary gas, the material heats up but cannot expand and cool. Nor can radiation carry away the heat fast enough.

The carbon and oxygen mixed in from the core catalyze the CNO cycle and thus speed up the fusion reactions. The rates of the nuclear reactions also depend very sensitively on the temperature, becoming 10^{16} to 10^{18} times faster when the temperature increases by a factor of 10. As the temperature deep within the accreted layers grows to more than 30 million kelvins, the material starts mixing turbulently with the zones above. The mixed region grows toward the surface, carrying with it both heat and nuclei from the interior. Within minutes the surface layers explode into space. They carry along with them fusion products and elements from the dwarf's core, accompanied by a tremendous increase in brightness.

Burning Out

The first few minutes of a nova explosion have never been observed. Our simulations predict that the surface temperature can exceed one million kelvins and that the hot gases are blown away at more than 5,000 kilometers (3,000 miles) per second. Because its volume increases suddenly, the gas cools. In a few hours the radiation it emits shifts from being primarily in x-rays to the lower-energy ultraviolet. At the same time, the surface area of the gas increases, making the nova brighter even as it becomes cooler. A spectacular transformation ensues.

Initially, the expanding shell consists of a hot, dense gas of electrons and ions—atoms missing one or more electrons. This gas is reasonably transparent. But as it expands, its temperature drops below 10,000 kelvins. The electrons start to recombine with the ions to form atoms that are missing only a few electrons. These atoms have many energy levels and can absorb tens of millions of individual wavelengths of light.

The most important absorbers have atomic numbers around 26, that of iron. The spectrum of light that they can absorb is extremely complex. These ions and atoms block most of the energy being radiated in the ultraviolet, which is where most of the energy is emitted at this phase. When we first studied this phase, with Peter H. Hauschildt, then at Arizona State University, and other collaborators, we called it the iron curtain. The energy absorbed by the curtain is reemitted at longer—optical and infrared—wavelengths.

The iron curtain was vividly confirmed by our first observations of V1974 Cygni. Within hours of its discovery George Sonneborn of the NASA Goddard Space Flight Center activated our Target of Opportunity program, which allows us to observe immediately with the IUE satellite when a bright nova occurs. Pointing the wonderfully maneuverable satellite at the nova, he obtained a series of ultraviolet spectra.

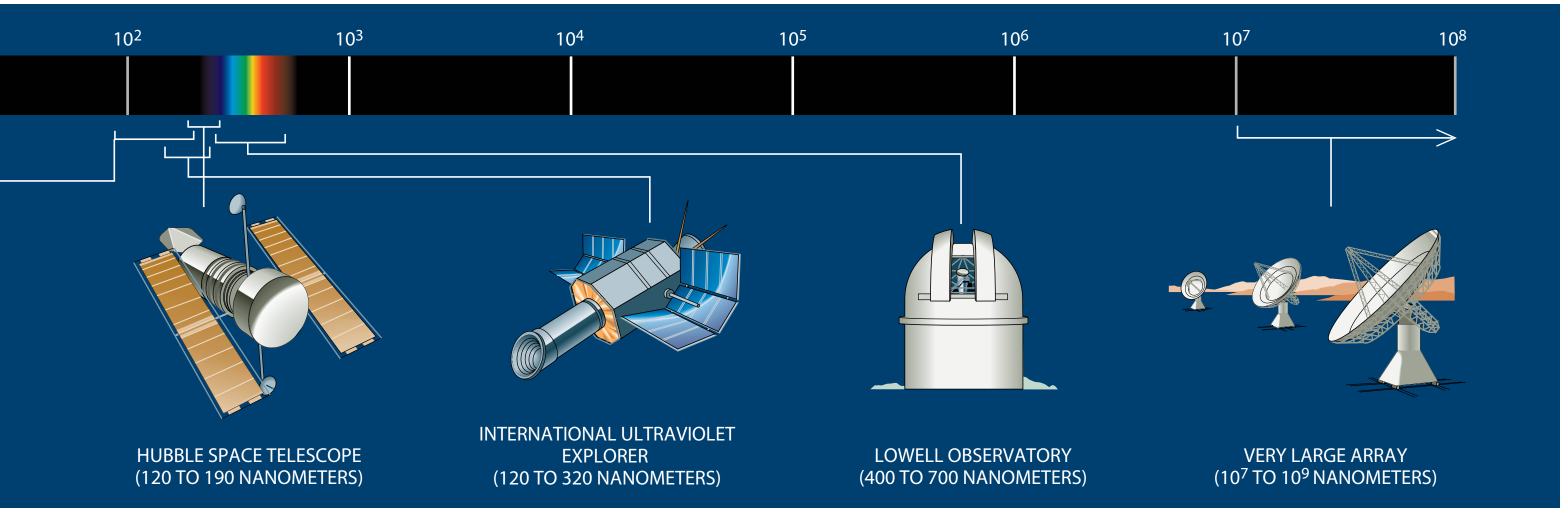
Within an hour we were able to observe that the nova's ultraviolet brightness had dropped slightly and that its optical brightness had risen. Astronomical change is measured, as a rule, in billions of years; it is rare to see evolution on such a short timescale. During the next two days, the ultraviolet radiation dropped to 3 percent of its original value. All the while the nova became optically brighter. As soon as the visual brightness peaked, the ultraviolet emissions bottomed out and began to climb.

The recovery comes from a second change in ionization. As the gas expands, its density drops. Then the iron group elements once again become ionized and hence transparent. Radiation now flows from the interior, enhancing the ionization and in turn the transparency. In effect, the iron curtain lifts, and ultraviolet light from the hot, deep layers penetrates through the outer layers. Within two months the ultraviolet brightness had climbed back up to its original value.

At the same time as the ultraviolet brightness increased, the visual brightness of the nova declined. The total (bolometric) brightness of the underlying star remained, however, virtually unchanged. This constant bolometric luminosity phase, predicted by our 1972 simulations, was finally confirmed in detail by observations of V1974 Cygni.

Anticipating that the radiation peak would continue toward shorter wavelengths, Ronald S. Polidan of the NASA Goddard Space Flight Center requested that Voyager 2, then flying beyond the orbit of Neptune, observe the spectra of V1974 Cygni. On April 27, 1992, the spacecraft detected the nova—the first to be seen in the far ultraviolet. Its brightness in this wavelength range increased during the observations.

The radiation peak continued to shift into shorter wavelengths. Using the ROSAT satellite, Joachim Krautter of Heidelberg Observatory, Hakki Ögelman of the University of Wisconsin and Starrfield had started observing the nova on April 22, 1992. The x-ray spectrum was very faint but included very high



energy photons. (We do not as yet know where the highest-energy photons come from.) Over the next year the x-ray brightness of V1974 Cygni steadily increased, mainly at low energies.

It seemed that a new source of x-rays had appeared, and it was steadily brightening. We realized that we were seeing through the thinning shell of ejected gas to the hot underlying white dwarf. Within three months the nova had become the brightest source of low-energy x-rays in the sky.

Such x-ray sources (called SSS, for supersoft sources) probably stay on for decades. To our surprise, the nova rapidly began to fade during the summer of 1993 and by December had become undetectable with ROSAT.

Fortunately, we were able to keep observing with the IUE. We found that the amount of highly ionized nitrogen was declining, which meant that the ions were recombining with electrons to form less ionized atoms. Furthermore, nitrogen ions that were missing four electrons were recombining faster than were the ions missing three electrons. Apparently the intense radiation that had been stripping the nitrogen of its electrons had vanished: the x-rays were indeed gone. To us, this absence could mean only that the white dwarf had consumed all its fuel and that the nuclear fusion on its surface had ceased.

The nova outburst had lasted about 18 months. The life span of a nova depends on the mass of the white dwarf that hosts it. A massive white dwarf compresses the accumulated gases more intensely. In that case, fusion starts early, and the fuel runs out quickly, causing the nova's life to be brief. Also, the explosion ejects much less matter than does one on a low-mass white dwarf. According to our models, the short life of V1974 Cygni implies that its mass was 20 to 30 percent greater than that of the sun. Theory predicts that about 10^{-5} solar mass should have been ejected from this kind of white dwarf. The observations imply that V1974 Cygni lost about five times this amount.

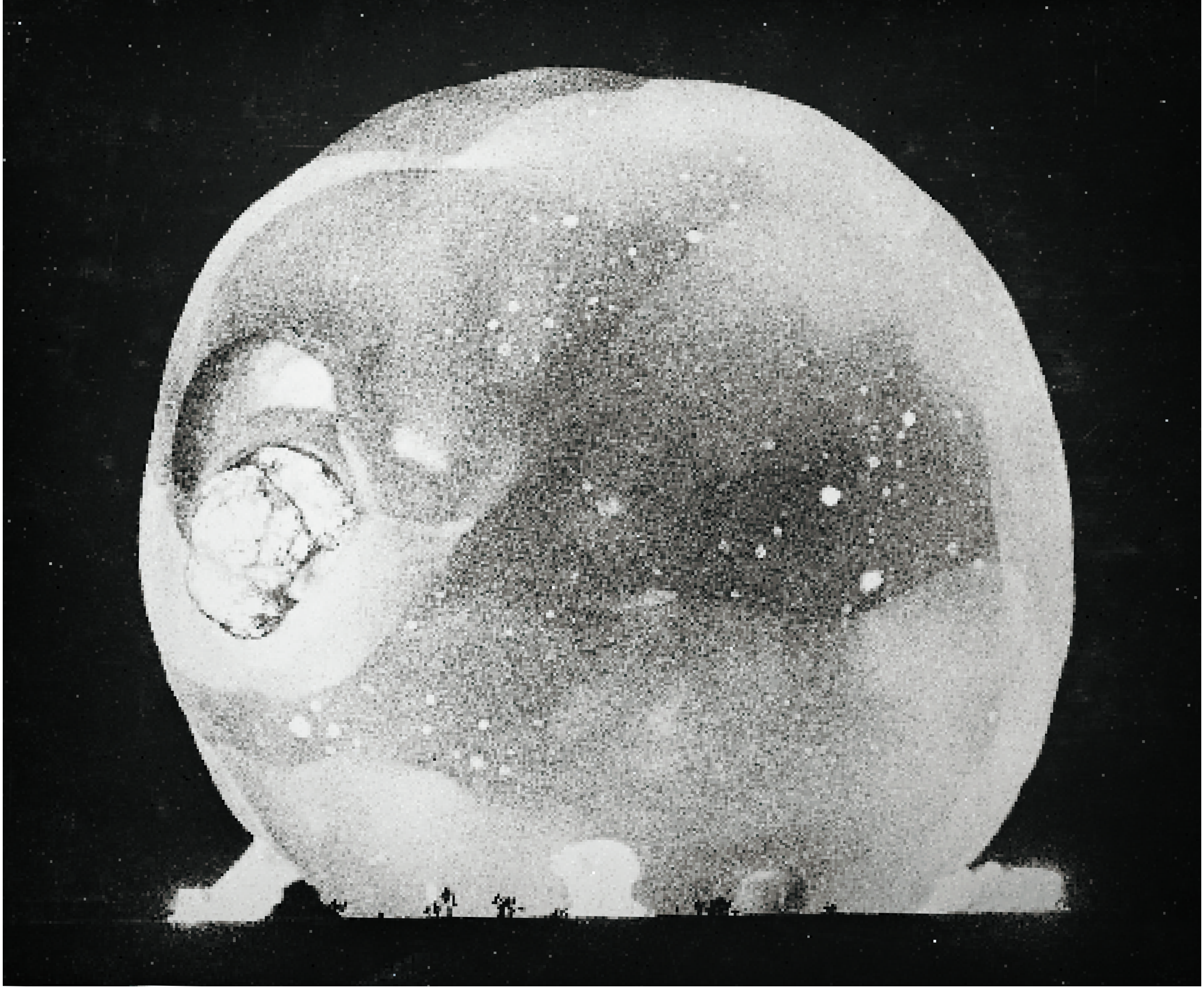
Clumpy Clues

Some hints to the explanation for this discrepancy may possibly be found in the knots. Our first clear view of the knots was on September 7, 1992, when we observed the nova with the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope. With this powerful instrument we obtained the highest-quality ultraviolet spectra ever for a nova. Each emission line showed evidence that the gas had been expelled in two stages. There was high-velocity gas that had been ejected uniformly and denser, slower-moving clumps.

Armed with the high-quality GHRS spectra, we reexamined the earlier data from the IUE. The spectra we had taken just after the iron curtain cleared also displayed the knots. This evidence indicates that the structures had been formed during the explosion. Looking again with the GHRS on April 1, 1993, we found the same clumps we had identified earlier, moving at the same speeds. The faster material had largely vanished, so we were now seeing completely through the ejected gas. This is the first time we have ever had such a clear view so early of the debris from a nova explosion. The knots appear to be deeply embedded within the ejecta. Now we need to understand what caused them and what they are made of.

The first indications of the composition of the ejecta had come around April 1, 1992, when the iron curtain finally lifted, leaving an intense spectrum with bright emission lines from carbon, nitrogen, oxygen and other abundant elements. Previously, we had encountered emission lines of this kind only in novae that took place on massive ONeMg white dwarfs. We conjectured that V1974 Cygni, too, belonged to this class. The idea also occurred to Thomas L. Hayward of Cornell University and Robert D. Gehrz of the University of Minnesota and their collaborators, who had just obtained infrared spectra of the nova using the five-meter telescope on Mount Palomar. They found the characteristic 12-micron line emitted by ionized neon. This line is normally very weak or absent in CO novae but is strong in ONeMg novae.

In the fall of 1993 the gases thinned enough so that Scott Austin of Arizona State University, R. Mark Wagner of Ohio State University and the two of us could finally use the optical and ultraviolet spectra to determine the chemical abundances of the debris. (While the gas was dense, the atoms collided with one another, thus complicating the spectra greatly.) We found large quantities of elements from the core, such as oxygen and neon. In our last observations with the GHRS, in September 1995, we directly observed one of the knots and confirmed that it contained at least 15 times more neon than solar material. We were also able to directly observe the white dwarf and confirm that it had turned off. These results demonstrate that we were indeed seeing core material from a white dwarf. In no other astronomical object can we see core gases blown into space where they can be studied and provide data on stellar death.



HAROLD EDGERTON

FIREBALL billows out a fraction of a second after an atomic bomb explosion at a Nevada test site. Its structure is very similar to the fireball from a nova. This photograph from the 1950s was taken by automatic instruments situated 32 kilometers away. In the foreground are Joshua trees, about to be incinerated. The intense heat melted desert sand into glass.

Another, related mystery pertains to the elements synthesized during the explosion. Achim Weiss of the Max Planck Institute for Astrophysics in Garching, Irit Idan and Giora Shaviv of the Technion University in Israel, Truran and Starrfield have calculated that ^{22}Na, an isotope of sodium with mass number 22, should be produced in an ONeMg nova. This isotope is radioactive, with a distinct pattern of gamma-ray emissions.

Our calculations indicate that V1974 Cygni produced large amounts of ^{22}Na. With the Compton Gamma Ray Observatory, we searched for the appropriate gamma rays in September 1993—but found none.

All these anomalies tell us that although we have come a long way in understanding nova explosions, we still have much to learn. We understand the thermonuclear reactions that produced the explosion. What is not so clear is the dynamics. Do the shell and the core mix while material is being accreted or during the last stages of the explosion?

Another mystery is the long-term effect of repeated nova outbursts on the evolution of the white dwarf. All nova binary systems go through the cycle of accretion and explosion many times. If parts of the core are shed during each outburst, then the mass of the white dwarf must be decreasing with repeated explosions. Does its mass become ultimately very small, or does something happen to stop any further outbursts?

Because of the brightness and slow evolution of its debris, we will be observing nova V1974 Cygni well into the 21st century. We hope the nova will supply some answers to the questions it has raised. SA

The Authors

SUMNER STARRFIELD and STEVEN N. SHORE have a particular fascination with stellar explosions. Starrfield obtained his Ph.D. at the University of California, Los Angeles, and since 1972 has been a professor at Arizona State University. Starrfield was the principal investigator for observing novae with the International Ultraviolet Explorer and the Compton Gamma Ray Observatory satellites. Shore received his Ph.D. in 1978 from the University of Toronto and now chairs the department of physics and astronomy at Indiana University, South Bend. He observed V1974 Cygni with the Goddard High Resolution Spectrograph, which was on board the Hubble Space Telescope. Shore serves on the editorial board of the *Encyclopedia of Physical Science and Technology* and is a scientific editor of the *Astrophysical Journal*. This article updates a version that appeared in *Scientific American* in January 1995.