A Fresh Look at a Familiar Supernova

Hubble views the Crab

By RON COWEN

In A.D. 1054, Chinese astronomers recorded the appearance of a celestial body so bright that for 3 weeks its glow remained visible, even in daylight. Although they considered their finding the debut of a "guest star," in truth the astronomers had witnessed a heavenly death, not a birth.

The fireworks they observed stemmed from a massive star some 6,000 light-years from Earth. This stellar body had ejected its outer layers in a giant explosion and collapsed its massive core to a volume so small that its density exceeded 16 billion tons per cubic inch.

Nearly 700 years after the Chinese stargazers reported this spectacle, English astronomer John Bevis pointed a telescope at the same patch of sky and found a brightly lit, gaseous object. Some 70 years later, William Herschel observed the body glowing in a blue light. In 1844, the Earl of Rosse wrote that the object resembled a crab and named the heavenly phenomenon the Crab nebula.

Today, this object, now known to be a supernova, ranks as one of the most frequently studied bodies in the sky. Indeed, many astronomers consider it a Rosetta stone for a variety of phenomena in high-energy astrophysics. Writes astronomer Kenneth Brecher of Boston University: "Much of what we know about the astrophysical origin of cosmic rays, synchrotron radiation, and heavy elements derives from our knowledge about the Crab nebula" *(Astronomy of the Ancients,* 1980, MIT Press).

But given the rich architecture of this exploded star and its remnant — a dense stellar core, a ballooning volume of strong magnetic fields and high-speed charged particles, and outlying filaments of gas — the complete structure of the Crab nebula has proved difficult to decipher.

"The problem with the Crab," says John J. Hester of Arizona State University in Tempe, "is that when you take images from the ground, the better and better the images you get, the more and more structure they reveal. Each advance [in imaging] provides you with new information, and you kind of wind up [having to keep] going back to the drawing board to interpret the data."

In other words, researchers haven't had sharp enough views of the Crab nebula to make a detailed portrait.

But recent observations with the repaired Hubble Space Telescope have changed that, Hester and his colleagues reported in June at a meeting of the American Astronomical Society in Minneapolis. Combining these new images with ground-based discoveries that include intriguing knots of material dubbed "argoknots," astronomers are rapidly gaining new insights into the evolution of this renowned supernova and the complex, often violent interactions of its parts.

"It appears that we have now resolved the lion's share of structure in the Crab," Hester says. "We're getting something that's approaching the penultimate look at the Crab nebula."

It's not hard to understand why the Crab has long fascinated astronomers. As Hester puts it, "The Crab has a little something to offer for everybody."

Astronomers who want to explore high-density matter need look no further than the heart of this supernova, which contains an extremely compact, rapidly rotating body called a neutron star — the remains of the massive star that exploded. Known as a pulsar, this spinning neutron star features twin, oppositely directed jets of radiation — including visible light and radio waves — that emanate from the star's poles and sweep past Earth like searchlights 30 times a second.

Researchers interested in the behavior of high-speed electrons observe outlying regions of the Crab. The pulsar's intense magnetic field, together with its rapid rotation, accelerates electrons, positrons, and perhaps heavier charged particles to nearly the speed of light and then drives them away in a fierce wind. As these speedy particles move out under the influence of the magnetic field, they emit a type of light called synchrotron radiation, which manifests itself in visible light as the blue glow recorded by Herschel.

Known as the synchrotron nebula, this ballooning cloud of tenuous, lightweight material fills much of the Crab. Powered by the pulsar, which continuously pumps out a new supply of high-speed charged particles, the nebula pushes against dense filaments of gas that lie along the outer reaches of the supernova.

These filaments contain heavy elements such as carbon, oxygen, nickel, and iron — atoms forged deep inside the massive star before it exploded. The production of such elements is critical because cosmologists believe that before the first generation of stars died out, the universe consisted only of hydrogen, helium, and trace amounts of lithium. All of the heavier elements formed in nuclear reactions inside stars and then spewed into space through such phenomena as stellar winds and supernova explosions.

Flung out into space during the massive star's violent death throes, the Crab's filaments — and those of other supernovas — helped seed the cosmos with the chemically enriched material needed to make stars like the sun and planets like Earth.

Notes Hester: "The reason that there's so much interest in the filaments of the Crab, their chemical composition, and the way they behave is that according to our current ideas, objects like these are an essential part of what allowed people and planets to come into existence."

The new Hubble pictures, taken with the telescope's second-generation wide-field and planetary camera, essentially fall into two categories of images. One set focuses on the synchrotron nebula and the pulsar, which radiate across a wide spectrum of wavelengths. The other group of images reveals the chemical composition and shape of the outlying gaseous filaments, which radiate only at the specific wavelengths characteristic of the atoms they contain.

Together, the pictures paint a detailed portrait of the Crab and how its various components interact, resolving structures as small as 200 astronomical units (AU). (One AU, the average distance between Earth and the sun, is about 150 million kilometers.)

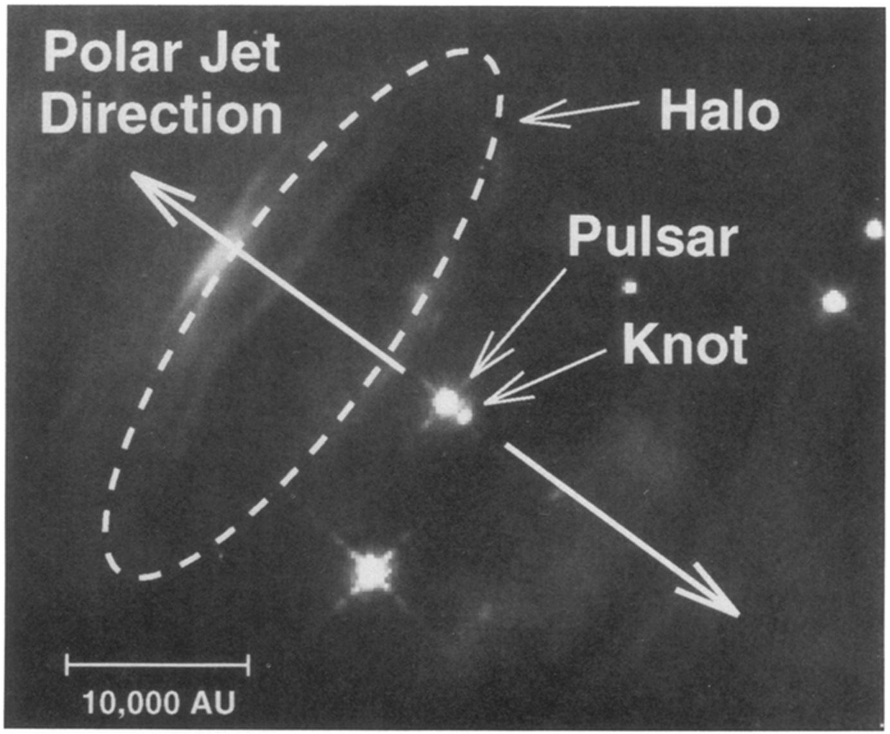
In examining Hubble photos of the synchrotron nebula, Hester and Arizona State University collaborator Paul Scowen found a bright knot of glowing material surprisingly close to the pulsar. The knot, which appears to line up with a jet of X rays that emanates from the pulsar, lies about 1,500 AU from the rapidly spinning neutron star.

In effect, notes Hester, the finding shows that the region where the Crab's pulsar and the surrounding synchrotron nebula start their violent interactions lies nearer to the pulsar than had ever been documented. The knot may signify a shock wave in one of the pulsar's two jets – a region where the wind of charged particles streaming away from one pole of the pulsar meets material in the surrounding nebula and piles up.

The knot indicates that "this is where the action begins" between the pulsar and the nebula, Hester says.

The repaired Hubble's ability to image smaller features and to discern faint bodies that lie near brighter ones enabled the researchers to make their discovery. "This object had never been seen before because it was always lost in the glare of the very bright pulsar," says Scowen.

A second discovery involves a group of wispy features previously observed with ground-based telescopes. The Hubble images show that the innermost wisps appear to form a halo of light around one of the pulsar's two jets.



Hester

Diagram shows two features of the Crab nebula supernova remnant discovered by the Hubble Space Telescope: a knot of emissions that is the closest known to the pulsar and a halo that surrounds one of the pulsar's two jets.

The origin of the halo remains a mystery, but its location – midway between one of the pulsar's polar jets and a strong wind coming from the pulsar's equator – is intriguing, Scowen notes. Finding such a feature may help astronomers probe the transition region between energy pouring out of the poles of the pulsar and its equator, he says.

"You can't get up close to a pulsar, even if one were close to the sun, because its environment is so extreme. The existence of the halo may serve as the next best thing – a probe of a very special region near this energetic body," says Hester.

It remains unclear why the wisps lie in the path of one of the jets but not the other. More generally, says Hester, it is unclear why the inner part of the Crab has so much asymmetry, with a bright knot seen on one side of the pulsar and the halo on the other.

Nonetheless, "the new data have provided a clearer glimpse of the pulsar environment, a glimpse that should have theoretical astronomers scratching their heads for some time to come," Scowen says.

The researchers also studied the outer reaches of the Crab. Observing the network of gaseous filaments, Hester and Scowen found that they formed a giant, three-dimensional patchwork, with cooler, denser regions embedded within hotter, more tenuous ones. In the team's false-color portrait, red fingers of cool, neutral oxygen are buried within the green of hot, doubly ionized oxygen and the blue of warm, singly ionized sulfur.

Though the regions of different temperatures vary in thickness from several hundred to 1,000 AU, most are in the range of 300 to 400 AU. The high-resolution images, adds Hester, offer something lacking in the fuzzier pictures taken from the ground: The filaments have sharp, definable edges.

The patchwork seen by Hubble, notes Hester, indicates that the standard way of modeling the filaments, as a one-dimensional structure, can no longer suffice. "When you study the Crab from the ground, you're [actually] averaging over very, very diverse physical conditions. That's the bad news. But now that we have these images... people who do models of the Crab filaments can begin to replace their speculations about what the structure of those filaments might be with real knowledge.

"As a result, we can better trace the chemical legacy that the Crab offers us."

Other images show that concentrations of dust reside throughout the supernova and appear to be far more pervasive than ground-based observations had indicated.

"It was surprising a few years ago when several researchers independently detected the presence of dust in the Crab, because traditionally it had been thought the Crab was surely far too violent an environment for dust to form," Hester notes.

In the Hubble images of the synchrotron nebula, the dusty regions stand out as dark, light-absorbing knots against the bright background of the nebula. Pictures of the filaments reveal that these knots coincide exactly with the places in the Crab where the gas is coolest and densest – the red cores consisting of neutral oxygen.

Hester and Scowen speculate that the hotter, more highly ionized parts of a given filament bear the brunt of the energetic radiation from the synchrotron nebula, shielding the cooler, denser cores from this dust-destroying ultraviolet light. Thus, dust may find a safe haven in many areas of the Crab despite the supernova's penchant for violent interactions.

Perhaps the most curious finding, says Hester, concerns the distribution of the filaments themselves. Rather than existing as a bunch of isolated filaments oriented in random directions, these projections reside throughout the supernova's perimeter. Moreover, all of them point inward, toward the center of the synchrotron nebula.

This geometry replicates a well-known pattern that results when, for example, a bottle of salad dressing is turned upside down. Ordinarily, because oil has a lower density than vinegar, the oil lies on top. When their positions are reversed, fingers of the vinegar begin to fall through the oil. Such a pattern, in the argot of fluid dynamics, is known as the Rayleigh-Taylor instability.

In the case of the Crab nebula, the dense filaments of gas ejected during the supernova explosion play the role of vinegar; the lightweight material of the synchrotron nebula plays the role of oil. When the billowing nebula pushes against the heavy filaments, it creates the fingerlike pattern seen by Hubble, Hester suggests.

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Science & Society

The high cost of having some babies...

Roughly 8.5 percent of U.S. married couples are infertile. Though that rate has not increased in recent years, the number of people who sought treatment between 1968 and 1982 nearly tripled, fueled in large measure by increasingly successful in vitro (test-tube) fertilization techniques.

But these treatments are expensive, as two studies document in the July 28 NEW ENGLAND JOURNAL OF MEDICINE.

The first studied the 1992 costs of a successful delivery of one or more babies following in vitro fertilization. Many couples undergo several cycles of egg harvesting, test-tube fertilization, and subsequent embryo implantation before a baby is born. The less fertile the couple, the more cycles they tend to require before giving birth. Overall, less than half of couples treated for infertility succeed in giving birth.

In a new analysis, Peter J. Neumann of the Project HOPE Center for Health Affairs in Bethesda, Md., and his colleagues find that the costs of having a baby climb from about $67,000 per delivery for couples undergoing one fertilization cycle to $114,000 per delivery after six cycles.

That's just the average cost. Certain forms of infertility can jack up the charges dramatically. For instance, when the mother is 40 or more years old and the father infertile, delivery costs climb from about $160,000 for one cycle of treatment to $800,000 for couples requiring six cycles.

Much of the high economic cost associated with in vitro fertilization traces to the higher proportion of multiple births that occur among treated couples, Neumann and his collaborators calculate. The reason? Multiple births are usually premature, with smaller and sicker babies who require more intensive – and expensive – care.

... gets higher by the numbers

A second study in the NEW ENGLAND JOURNAL OF MEDICINE shows why hospital costs multiply for each additional child. Among 13,206 pregnant women who delivered at Boston's Brigham and Women's Hospital between 1986 and 1991, single babies remained hospitalized 4.6 days on average; twins typically stayed 8.2 days. Births involving more babies involved even longer stays. Moreover, 15 percent of single babies needed intensive care, compared to roughly half the twins and three-quarters of triplets, quadruplets, and quintuplets, say Tamara L. Callahan of Massachusetts General Hospital and her coworkers. Multiple births also increased the mother's need for care.

In the end, after accounting for a mother's age, race, and type of insurance, Callahan's group found that hospital charges for a single baby totaled about $9,850. By contrast, twins incurred average charges of $37,950 ($18,975 per baby), and the birth of triplets cost $109,765 ($36,588 per baby).

One-third of the twins and three-quarters of the triplets in the study were born to couples treated for infertility. Indeed, Callahan's team estimates that if each multiple pregnancy had involved a single baby, "the [annual health care] savings would have been more than $3 million in this one hospital." And as they did not factor in the additional postdischarge costs typically associated with twins and triplets, these figures probably understate the total costs of multiple births.

With health care funds tight, these figures raise several ethical issues, the researchers say. For example, who should have access to expensive fertility treatments? Who should pay the bill? Moreover, because not all fertility treatments run the same risk of fostering multiple births, should physicians focus on those most likely to result in a single baby?

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The ends of the filaments that resist the outward pressure exerted by this synchrotron nebula point down into the nebula; they are colder, denser, and move more slowly, he explains. The ends carried aloft by the nebula's pressure are warmer, more tenuous, and move faster.

"People had speculated that this sort of pattern might be going on in the Crab nebula, but the surprise is that when you in fact look at the Crab – *everywhere* that you look – you see this same structure," he says. "It turns out that this interface between the synchrotron nebula, being powered by the pulsar, and the filaments, the stuff that was ejected by the supernova explosion ... is the dominant organizing process going on in the Crab nebula."

This geometric pattern isn't the only new evidence that the various parts of the Crab are inextricably linked, he adds. Astronomers have monitored for about 2 decades the rate at which the pulsar is gradually slowing down.

Data from Hubble, in combination with the ground-based observations, now suggest that as the pulsar loses rotational energy, it transfers a significant amount of that energy to the filaments. The pulsar is the source of the extra pressure exerted by the ballooning synchrotron nebula on the filaments. As a result, the filaments receive an extra kick, or acceleration, comparable to the energy lost by the pulsar, Hester says.

"If you want to understand the pulsar and the synchrotron nebula, or if you want to understand the filaments, you have to worry about their interaction," he concludes.

The Hubble findings may also shed light on new ground-based findings that a lineup of 11 knots extends more than halfway across the Crab. At the June meeting, Stephen S. Lawrence and Gordon M. MacAlpine of the University of Michigan in Ann Arbor reported that the newly discovered knots show extremely high emissions by argon ions.

Images of the knots were taken with a 2.4-meter telescope at the Michigan-Dartmouth-MIT Observatory atop Kitt Peak in Arizona. The astronomers obtained spectra of the knots, which revealed the unusually intense argon emission, using the 4.5-meter Multiple Mirror Telescope near Amado, Ariz.

The explanation for these argoknots is unknown. The enhanced argon emission could stem from argon gas that congregates in clumps. Alternatively, the radiation could be caused by some process that selectively stimulates ordinary concentrations of argon to emit high-intensity radiation.

A comparison of the ground-based data with the Hubble images suggests that the argon emission originates in those parts of the filaments that poke farthest into the synchrotron nebula. This dovetails with ground-based measurements of the velocity of the argoknots, which show that they move relatively slowly.

Hester speculates that the location of the argoknots indicates that they do not consist of unusually high concentrations of argon but rather are subject to some kind of special stimulation that triggers the observed radiation. Lawrence and MacAlpine note that the regions within each knot that lie closest to the pulsar have the strongest argon emission. Based on this finding, they suggest in the Sept. 10 ASTROPHYSICAL JOURNAL LETTERS that the pulsar triggers the enhanced emission.

The argoknot story, Hester adds, highlights the importance of using ground-based data in conjunction with the Hubble images. Armed with new information from telescopes on the ground and in space, scientists studying the Crab are taking a fresh, more intimate look at an old celestial phenomenon.

And in the processs, Hester says, astronomers are on the verge of putting together "a well-rounded picture of one of the most important objects in modern astrophysics." □