SS 433, What Are You?

Not one star but two, SS 433 continues to baffle astronomers with its antics

The eccentric star sits smack in the center of a cloud that resembles the debris from an exploded star. To radio astronomers it has features commonly found in energetic galaxies. Its x-ray output mimics that of a pair of stars, one of which is losing mass rapidly to its companion. Yet its radiation in visible light is unlike that of anything known. The star is known as Stephenson-Sanduleak 433—SS 433.

Its odd visible spectrum includes several bright emission lines that change wavelength from night to night. When he described these lines early last year, Bruce Margon of the University of California, Los Angeles (UCLA), piqued the curiosity of astronomers around the world. According to newspapers, SS 433 is simultaneously coming and going at over one-quarter the speed of light. Astronomers doubt that the star itself is schizophrenic, however. Instead they propose that two streams of gas near the star whiz in opposite directions.

Although SS 433 is intriguing as a curiosity, ultimately it may be a Rosetta stone for astrophysics. Experts hope that it will provide clues to the way jets of gas are sprayed from many energetic galaxies that emit radio waves. Stephenson-Sanduleak 433 may have "the first jets we can study with an optical telescope to get information about gas temperature and other clues to how jets work," says Kris Davidson of the University of Minnesota. Explaining the jets in the radio galaxies may boil down to explaining the gas streaming from SS 433—a challenge in itself.

The story of SS 433 reads like an astronomical detective story. Clues gathered during nearly 2 years of intensive monitoring are helping to unravel the mysteries of the source. Researchers now know how the star behaves, and they have some ideas about what it is. They believe that they are on the threshold of viewing directly the postulated high-speed jets of gas. As yet there is no consensus about how such gas streams, if they exist, might be produced, although speculations abound.

Bruce Stephenson and Nicholas Sanduleak of Case Western Reserve University discovered the star 20 years ago. It is the 433rd entry in their 1977 list of unusual stars whose spectra include strong emission lines from hydrogen atoms. Stephenson says they delayed listing the star because "its emission was so strong that we thought it must be known already."

That three groups independently and nearly simultaneously rediscovered SS 433 in mid-1978 hinted of the star's impending preeminence. The rise to fame started when one of the rediscoverers, David Clark of Royal Greenwich Observatory, discussed the star with Margon. "By extraordinarily good luck I was in England at the Royal Observatory the day after Clark got back from the Anglo-Australian Telescope [in Australia, where Clark briefly observed the object]," Margon explains. "I was rained out of observing, and got to chatting with Clark, who said 'see what an exciting thing we just found.' " At the time, Clark was unaware that the star had been discovered previously.

Clark was excited because he suspected that the star might be the remains of the supernova, the exploded star, that produced the debris cloud. The position of SS 433 in the center of the cloud, together with its known radio wave emission and the radiation from neutral hydrogen, pointed toward that possibility. The star was clearly unusual. Since strange stars tend to be odd in many respects, Clark surmised that SS 433 was the source of x-rays coming from its patch of sky. Yet, neither Clark nor Stephenson and Sanduleak guessed that the star was as exotic as it has proved to be.

Clark's description intrigued Margon, whose specialty is the study of visible light radiation from strong x-ray sources in our galaxy. Most such sources are star pairs. One of the stars emits visible light and sheds gas, which is swept up by the companion to fuel the emission of x-rays. Usually the companion is a superdense neutron star or perhaps an even denser black hole. By studying the visible light output of the normal star, Margon gets clues to the nature of its cohort and the ways x-rays are produced. When Clark suggested that SS 433 might be a strong x-ray source, Margon returned to California eager to check it out.

The first spectrum he took of the star included strong emission lines at strange wavelengths—radiation that no common elements or ions emit. "If you see strange lines in a spectrum, normally you don't think anything of it," says Margon. But in this case the lines were nearly as strong as the brightest line in the spectrum, a line from neutral hydrogen. Either the element producing the strange lines was nearly as abundant as hydrogen, by far the most common element in the universe, or a bizarre process was amplifying some normally weak lines from a rare element. Margon was particularly intrigued because Clark had not mentioned such prominent, unidentified lines.

When Margon looked again, the spectrum had changed. There were still mysterious lines, but they were at different wavelengths than before. Such extraordinary behavior was baffling, and he quickly alerted other astronomers to his findings.

Since Margon's announcement, SS 433 has been one of the most watched objects in the sky. It is bright enough that a spectrum can be recorded in only a few minutes with a large telescope, and astronomers from around the world have been willing to sacrifice such brief snatches of their telescope time to deciphering the mysterious star.

As a result of all the attention, researchers soon divined that the strange spectral lines are emitted by neutral hydrogen. They are enormously shifted in wavelength, because the hydrogen is traveling at extremely high velocity—over one-quarter the speed of light. Because of the Doppler effect, radiation from gas approaching the earth appears bluer than normal, while emissions from gas heading away are reddened.

In SS 433, each hydrogen emission line has both a bluer and a redder so-called satellite, so the star includes both approaching and receding gas. Early last year, Mordehai Milgrom of the Weizmann Institute in Israel inferred that the two gas streams are linked and head in exactly opposite directions. The spectral

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lines change gradually in wavelength because the direction of gas flow, and hence the amount of Doppler shift, changes steadily. Margon pegged the period of this wobble in direction at 164 days.

Since most researchers focused their attention on the bizarre, moving spectral lines, they overlooked a big clue to the nature of the source that was hiding in the more normal emissions of the star. Even the apparently stationary spectral lines change in wavelength. David Crampton, Anne Cowley, and John Hutchings of the Dominion Astrophysical Observatory in Victoria, British Columbia, observed very slight Doppler shifts in these lines. The source approaches and then recedes at speeds up to 75 kilometers per second, says Crampton, and a full cycle takes about 13 days.

Such behavior is the signature of a binary, a two-star system similar to many of the strong x-ray sources in our galaxy. In this case, the two stars orbit each other in about 13 days.

But SS 433 does not behave like a normal x-ray binary. In addition to radiating some x-rays, although less than is typical in such binaries, it spends a lot of energy—roughly a million times the energy radiated by the sun—accelerating gas. The questions baffling theorists are why and how. At present, two very different mechanisms are considered promising.

With the discovery that SS 433 is a binary rather than a lone star, theorists breathed a sigh of relief. In the most popular type of model, which was first advocated by Martin Rees and Andy Fabian of Cambridge University, the high-speed gas streams away from SS 433 in two jets. Finding a source for the gas was a challenge that the star pair met easily. One of the stars sheds the gas, which its companion flings into space. The companion is believed to be either a neutron star or a black hole.

In many jet models, the reason gas is ejected from the system is that too much is falling toward the compact companion. Normally, material flowing between the two stars would be converted into x-rays and added to the superdense star. But in the case of SS 433, so much mass is transferred that x-rays are extremely intense. This radiation "pushes the infalling matter up faster than gravity pulls it down," explains Jonathan Katz of UCLA. The only place the expelled gas can go is out of the plane containing the two stars and all the material flowing between them. It travels just fast enough (about one-quarter the speed of light) to escape the gravitational pull of the compact object. According to Craig Sarazin of the University of Virginia, about 1000 times as much mass is transferred in SS 433 than is normal in x-ray binaries.

Theorists have offered several possible explanations for the beams' wobbling. Strong tidal interactions between the two stars could cause the wobble, say Edward van den Heuvel of the University of Amsterdam, Jeremiah Ostriker of Princeton University, and Jacobus Petterson of the University of Illinois, Urbana. Alternatively, Mitchell Begel-

Carbon Budget Not So out of Whack

Every year plants exchange more than 100 billion metric tons of carbon with the atmosphere in the form of carbon dioxide. The ocean spews forth and reabsorbs almost as much carbon dioxide as it churns up its deepest waters and as its surface waters warm and cool with the seasons. Even these mammoth quantities seem insignificant next to the thousands of billions of tons of carbon stored in the oceans, plants, and soil of Earth.

The task of measuring small changes in these flows of carbon dioxide through the atmosphere is difficult but necessary. Predictions of the possibly catastrophic climatic warming that could result from man's increasing the carbon dioxide content of the atmosphere require such measurements. Among those trillions of tons of carbon, researchers are trying to determine whether human activities each year are releasing only 5 billion tons (5 gigatons) or perhaps as much as 10 or 15 gigatons of carbon as carbon dioxide to the atmosphere. Everyone agrees that an amount equivalent to about half of the 5 gigatons of fossil fuel carbon now burned each year ends up in the atmosphere as carbon dioxide. Many oceanographers have thought that most of the rest dissolves in the surface waters of the ocean. That would leave all of the anthropogenic carbon dioxide accounted for and the cycle balanced, except that some terrestrial biologists suggested a few years ago that the destruction of forests, especially the increasing exploitation of the tropical forests, adds even more carbon dioxide to the cycle (*Science*, 30 September 1977, p. 1352). Initial estimates of the land's contribution ranged as high as twice the size of the fossil fuel source, but oceanographers recoiled at the suggestion of putting all of that carbon into the ocean. It could not be done, they said.

Few new field data have been gathered, and the oceanographers and biologists still do not agree, but more leisurely analyses of the available data have narrowed the range of disagreement, primarily by shrinking the possible terrestrial source. In one recent study of the biosphere's role in the carbon cycle, Wolfgang Seiler of the Max Planck Institute for Chemistry in Mainz and Paul Crutzen of the National Center for Atmospheric Research in Boulder concluded that the land may be acting as either a small source of carbon dioxide or as a small sink by absorbing more carbon dioxide than it gives off.

In particular, Seiler and Crutzen considered how fires, such as those used in the slash-and-burn agriculture of the tropics, wild fires, the burning of wood for fuel, and the clearing of land for urbanization, could affect the conversion of plants into carbon dioxide. For the first time, Seiler and Crutzen tried to account for the carbon preserved as charcoal following a fire. They estimated that this decay-resistant form of carbon might provide a sink, rather than a source, for 0.5 to 1.7 gigatons of the carbon burned each year. Taking account of other losses and gains, such as the oxidation of organic soils exposed by farming and reforestation of cleared areas, they concluded that the land could be either gaining or losing as much as 2 gigatons of carbon each year.

Although it is a significant fraction of the 5 gigatons released from fossil fuels, a maximum of 2 gigatons per year is small compared with the estimate of 4 to 8 gigatons per year (with a possible range of 2 to 18 gigatons) offered several years ago by George Woodwell of the Marine Biological Laboratory and his colleagues. But that figure too may be shrinking. In a summary paper presented at a Department of Energy research conference in Washington in May, it was reported that Woodwell's current best, though

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mann of the University of California, Berkeley, and Sarazin speculate that the wobble may be due to relativistic effects that warp space near the compact object.

The jets from SS 433 may be narrow because the gas squirts out through "nozzles," say Davidson and Richard McCray of the Joint Institute for Laboratory Astrophysics in Boulder. According to their model, excess mass shed by the more normal star spirals toward, but does not reach, the compact object. ("I believe it is a neutron star, but Kris seems to favor a black hole," says McCray. Even collaborators do not agree completely on SS 433.) Instead the gas forms a dense cloud, the inner edge of which is shaped like two nozzles aimed in opposite directions out of the plane of the two stars. "Gas evaporates into the nozzles," says Davidson, where it is accelerated outward by the pressure of radiation.

In the nozzles the streaming gas is far too hot for any neutral hydrogen to exist and emit the spectral lines that won SS 433 its fame. After emerging from the nozzles, however, the gas cools, and hydrogen ions combine with electrons.

"The reason the jets emit strongly is that they are rubbing against a stellar wind from the normal star," explains McCray. Each atom is ionized repeatedly by friction between the jets and the much slower gas of the wind. Each time an ion recombines with an electron, the newly formed atom emits the characteristic radiation as the electron cascades toward its ground state. McCray estimates that the region where this process occurs is about 1 billion kilometers long.

Both the means of accelerating the gas and its direction of motion set one model apart from the popular jet models. George Collins II, Gerald Newsom, and Richard Boyd of Ohio State University propose that the strong magnetic field of one of the stars, rather than the pressure of radiation, pushes the emitting gas. And the gas, riding the rotating magnetic field, whizzes around the binary, not away from it.

According to the Ohio State model, streams of ions blowing out from the magnetic poles of one of the stars collide in two regions on opposite sides of the binary. The moving spectral lines are emitted by the high-density, cool gas where the streams merge. As the star spins, the emitting regions circle the binary to trace out a ring. Since the ring is huge—30 times the diameter of the solar system, says Collins—and the gas takes about 164 days to orbit the binary, it cruises faster than one-quarter the speed of light.

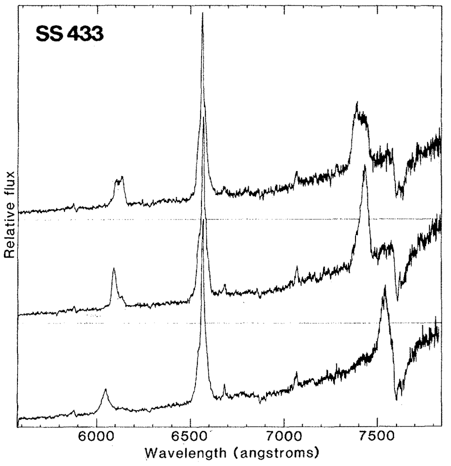
The sheer size of the ring has implications that may allow this model to be tested by observations. Light emitted from the far side of the ring takes about 4½ days longer to reach the earth than light emitted from the near side. Thus signals emitted simultaneously from the two emitting regions may be received at different times by telescopes. The time lag will vary as the two regions circle around the ring. According to Collins, a preliminary analysis of published data

not final, estimate for the 1970 release is 2 to 4 gigatons of carbon. "We can't rule out the 8 gigatons per year yet," says Woodwell, "but I would guess, and it's only a guess, that it's less than 8 and more than 2 gigatons per year. We're certainly ruling out the extreme number of 18."

Many terrestrial biologists are thinking about smaller releases of about 2 gigatons per year, citing a number of recent studies that lend support for a smaller contribution from the land. For example, Jerry Olson of the Environmental Sciences Division of the Oak Ridge National Laboratory estimates that living land plants contain only 560 gigatons of carbon rather than the once generally accepted 800 gigatons, which would mean lower fluxes of carbon dioxide from the exploitation of forests. The mass of plants actually being converted into carbon dioxide might be even smaller, according to Charles Hall of Cornell University, because as much as half of the forest being cleared in the tropics may not be dense virgin stands of trees but rather thinner stands that grew back since an earlier clearing. In addition, the carbon dioxide that is being released in the tropics is probably partially compensated for by the growth of temperate forests, according to the final report of a workshop conducted by the Institute of Ecology in Indianapolis. The temperate forests, which were extensively cleared in the 19th century, now appear to be regrowing fast enough to store about 1 gigaton of carbon per year, according to the workshop report.

While the biospheric source has been shrinking, oceanographers have continued to refine their estimates of how fast the ocean can absorb carbon dioxide from the atmosphere. Although oceanographers no longer suggest that the terrestrial biosphere must absorb much carbon dioxide, they cannot find much room in the ocean to place carbon dioxide from a terrestrial source. By tracing the path of nuclear bomb debris from the surface into deeper waters, and by using other techniques, Wallace Broecker of the Lamont-Doherty Geological Observatory has calculated that about 37 percent of the fossil fuel carbon dioxide released since 1958 could have been absorbed. Although Broecker and his colleagues are still adamant about the impossibility of dissolving several extra gigatons of biospheric carbon in the ocean, Broecker concedes that as much as 0.5 gigaton per year from a terrestrial source might be accommodated in the ocean. "One gigaton would be pushing it, but I suppose it could be possible," he says. Robert Bacastow of Scripps Institution of Oceanography reports that the ocean models he and Charles Keeling of Scripps work with do not allow a much larger terrestrial source than Broecker's does.

Although oceanographers and terrestrial biologists are beginning to talk about numbers in the same general range, a gap remains and errors in the estimates are still large. Some possible small sinks for carbon dioxide that could help close the gap are now being given serious consideration. The oceanographers will also be collecting crucial new data next year in the northern North Atlantic under the Transient Tracers program. No equivalent program for gathering data from the more complex terrestrial biosphere exists yet. The counteracting effects over the last few decades of resurging temperate forests and accelerating tropical forest clearing may have minimized the role of the terrestrial biosphere in the carbon dioxide problem, but researchers now realize that a land source could become a major factor as increasing population and the increasing cost of fossil fuels put greater pressure on the world's forests.—RICHARD A. KERR



The spectrum of SS 433 changed markedly from 23 October 1978 (top) to the 24th (center) to the 26th (bottom). This odd behavior triggered the brouhaha about the star. [Source: Bruce Margon, University of California, Los Angeles]

confirms this effect, but other researchers remain skeptical. "If we are wrong, there are other things in life to do," he philosophizes.

With the gas circling the binary and remaining in the emitting region perhaps for several revolutions, it is easy to justify the remarkable brightness of the moving emission lines, says Newsom. The gas in the ring "can be used over and over again," he explains. In the jet models gas passes through the emitting region only once, and while each hydrogen atom might emit several times, a large amount of gas must flow through the jets to account for the brightness.

There is a way to produce bright emissions without requiring excessive amounts of gas to be expelled in the beams of the jet models, say Davidson and McCray. They envision that the jets are lumpy, and most of the radiation comes from material that is roughly 1000 times denser than average. Since the ability of gas to radiate increases with the square of the density of the gas, "you don't need as much stuff if you have it in high density lumps" as you would if the gas were homogeneous, McCray explains.

Unfortunately, neither the billion-kilometer-long jet nor the 100-times-larger ring can be distinguished on photographs of SS 433. The star is about 10,000 light-years away, and at that distance, the jets and ring are too small to be resolved by optical telescopes. But radio astronomers, who as a group favor the jet models, have hopes of seeing the beams directly.

"Tantalizing signs of spiraling jets" show up in maps of the radio wave emission of SS 433, says Robert Hjellming, of the National Radio Astronomy Observatory's Very Large Array (VLA) radio telescope in New Mexico. Researchers expect the jets to appear twisted because their aim changes as the source wobbles. The VLA achieves excellent spatial resolution by combining the radio signals recorded by 27 antennas arranged along three spokes of a 35-kilometer circle in the desert. (Currently 24 of the antennas are operating.) Hjellming and his colleague Kenneth Johnston of the Naval Research Laboratory in Washington, D.C., have aimed the VLA at SS 433 roughly once a month since last July.

Hjellming and Johnston interpret their results cautiously. Although "there are significant features in every map that are different each time," says Hjellming, the changes in the maps may not reflect changes in SS 433 caused as the jets sweep around. Instead, both the changes and the signs of spiraling jets may be artifacts created by erratic fluctuations in the radio brightness of SS 433. Currently, Hjellming and Johnston are combing through their data to untangle the effects of these fluctuations—a tedious process.

Although radio astronomers have not yet captured the small, high-speed beams of gas or seen them wobbling, they do detect elongations in the shape of SS 433 that many experts attribute to the action of the jets. On every spatial scale between the 10-billion-kilometer resolution of the finest maps and the quadrillion-kilometer size of the putative supernova remnant, the elongations are aimed in precisely the same direction. Many experts interpret the elongations as emissions produced when the jets plow into surrounding interstellar matter.

It is "dramatic that the structure stays well aligned over such a broad scale," remarks Robert Preston, a radio astronomer at the Jet Propulsion Laboratory. In this regard, SS 433 is an "amazing look-alike to energetic radio galaxies," he continues. This resemblance prompts astronomers to wonder whether those galaxies operate the same way as SS 433.

That the radio elongations align with lobes on the alleged supernova remnant has caused many astronomers to question whether that cloud, named W50, is really the remains of an exploded star. "SS 433 definitely has something to do with W50," says Preston. But there is no consensus on whether SS 433 is a product of the stellar explosion that created W50, or whether the apparent debris cloud is a result of the action of SS 433.

Sarazin describes W50 as a "beam bag, because it is the thing that catches the beams." He and Begelmann suspect that the entire cloud may have been blown up by the jets from SS 433. Many other researchers believe that at least the ears of W50 were inflated by the streaming gas.

Images made recently by the x-ray telescope on the Einstein Observatory (the second High Energy Astronomy Observatory; see *Science*, 6 July 1979) affirm the link between SS 433 and the knobs on W50. According to Ernest Seaquist of the University of Toronto, "faint but unmistakable features like plumes or columns extend outward from the point source [SS 433] precisely in the direction of the lobes of W50."

Chemically and structurally, however, W50 "looks very much like a supernova remnant," says Sidney van den Bergh, director of the Dominion Astrophysical Observatory. Van den Bergh's data, together with the uncanny alignment of all the jets and elongations detected, suggest that the relationship between SS 433 and W50 is not simple. If W50 is a remnant, perhaps SS 433 also formed when the star exploded. Subsequent action by the jets may have carved out the ears in the debris cloud. If SS 433 is the remains of an exploded star, then it is a new type of remains, perhaps a short-lived phase that could provide clues to the supernova process.

Observations continue and the quality of the data is improving as astronomers hone their techniques to challenge the mysteries of SS 433. More surprises may be in store, but researchers expect ultimately to figure out what the star does and how it does it. It will be interesting to see which, if any, of the current ideas hold up.

—BEVERLY KARPLUS HARTLINE

Additional Reading

1. B. Margon, "The peculiar object SS 433," in *Proceedings of the NATO Advanced Study Institute on Galactic X-ray Sources*, P. Laskarides and P. Sanford, Eds. (Wiley, New York, fall 1980) (review paper).
2. B. Margon, S. A. Grandi, R. A. Downes, "The 164- and 13-day periods of SS 433: Confirmation of the kinematic model," *Astrophys. J.* **241** (1 October 1980) (reviews optical observations).
3. K. Davidson and R. McCray, "SS 433 as a prototype of astrophysical jets,' " *ibid.* (1 November 1980) (summarizes current thoughts and physical constraints on the jet models).