# The Bizarre Spectrum of SS 433

*Displaced emission lines found in the spectrum of this extraordinary stellar object suggest that it is spewing two narrow high-speed jets of matter in opposite directions. How can such behavior be explained?*

by Bruce Margon

With 100 billion stars in the Milky Way there is not much room for individuality. Virtually every phenomenon in the galaxy has a chance of happening more than once. Hence "unique" is not a term often applicable in stellar astronomy. Even some highly unusual astronomical objects have been found to have analogues; for example, the Crab Nebula, the spectacular remnant of a supernova explosion that was observed in A.D. 1054, apparently has two or three counterparts elsewhere in the galaxy. Over the past two years, however, observations have accumulated on a stellar object that probably is deserving of the term unique. The object, known as SS 433, appears to be ejecting two very narrow jets of matter in opposite directions at incredibly high velocities. No other star has ever been observed to behave in such a manner.

SS 433 is a fascinating object for many reasons, not the least of which is the fact that it was discovered independently several times in the past two decades, although each time its discoverers failed to recognize its truly exotic character. The object emits an exceptional pattern of radiation in several different parts of the electromagnetic spectrum (at wavelengths corresponding to visible light, radio waves and X rays), and each of these peculiarities had been individually noted over the years. It was not until quite recently, however, that a comprehensive picture of SS 433 began to emerge. It is instructive to trace the early history of the observations, in order to see how close the earlier investigators came to detecting the unique properties of the object.

The first pertinent clues were obtained in the early 1960's when astronomers at Case Western Reserve University conducted a systematic survey aimed at discovering certain types of faint stars near the central plane of our galaxy. The particular telescopic technique they employed incorporated an objective prism, a light-dispersing optical element that smears stellar images on a photographic plate into tiny trails representing the visible spectrum of the starlight. Unlike the more conventional techniques of astronomical spectroscopy, in which the light from a single star is passed through a narrow slit near the focus of the telescope and then dispersed over a considerable part of a photographic plate, the objective-prism technique separates the starlight by wavelength only slightly. It does so simultaneously for every visible stellar image in the field of view, however, rather than for one star at a time. In this way very crude spectrograms, suitable mainly for classifying different types of objects, can be obtained for large numbers of stars with only a modest investment of precious telescope time.

The Case survey was specifically designed to find new stars with emission lines in their spectra. The existence of such lines forms the basis of a versatile diagnostic technique common to many areas of physics and chemistry. When the electrons bound to the atoms in any diffuse gas are excited to higher "orbital" energy states, either through collisions with other particles or through radiative interactions, their subsequent de-excitation creates new photons, or light quanta, at certain discrete wavelengths that are determined by the energy difference between the orbital states and hence by the electronic structure of the particular element. The appearance in a spectrogram of these lines (so named because they manifest themselves as a linear darkening at a particular wavelength on the exposed photographic negative) can then serve as a highly specific probe of the physical conditions in the emitting gas. The precise wavelength of such a line, for example, is an unambiguous indicator of the original light-emitting chemical element, since it bears the memory of the atom's electronic structure.

Objective-prism studies such as those carried out by the Case workers have shown that perhaps as many as 10 percent of all stars produce emission lines characteristic of a hot, excited gas; such a gas is thought to exist in a diffuse outer layer surrounding an otherwise normal star. There are many possible reasons for this abnormal situation, and they vary from star to star. Emission lines are often found, for example, in association with very young stars and very old stars. On occasion they are also identified with a stable middle-aged star.

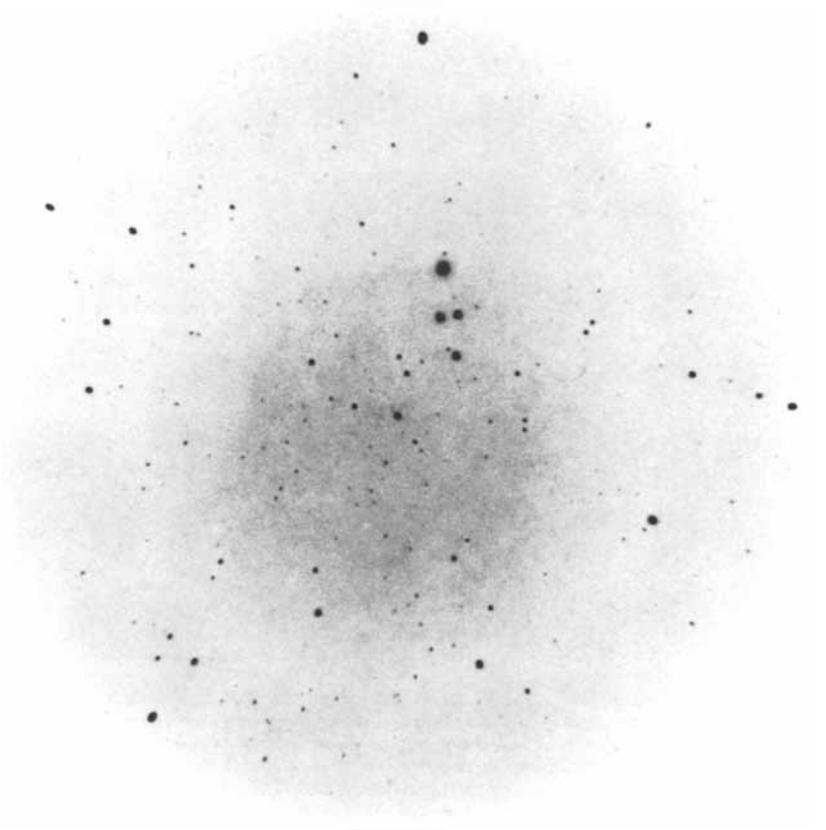
One of the plates exposed by the Case workers was centered on the constellation Aquila in the midst of the Milky Way; many strong emission-line objects were visible on the plate. In 1977 C. Bruce Stephenson and Nicholas Sanduleak published a list of the emission-line objects in the area; the 433rd entry on their list was the star now known as SS 433. Stephenson and Sanduleak had no reason for singling out SS 433 as being particularly different from the hundreds of other emission-line stars identified in their survey; spectroscopic data more detailed than those that could be obtained by the objective-prism technique would be needed for the purpose. Indeed, one of the primary goals of surveys such as the Case effort is to stimulate future detailed observations of interesting-looking objects. As it turned out, with SS 433 Stephenson and Sanduleak succeeded in this respect beyond their fondest dreams.

With an apparent brightness equivalent to that of a 14th-magnitude star, SS 433 is more than 1,000 times too faint to be visible to the unaided eye. It is an easy target for spectroscopic observations, however, even with a rather small telescope. The follow-up observations might well have been stimulated as early as 1975, when Lawrence Krumenaker, another Case astronomer, published a short paper that appeared before the publication of the Stephenson-Sanduleak catalogue. The paper mentioned a small subset of emission-line stars from the full survey, including the then-anonymous SS 433, and it gave the celestial coordinates and charts needed to enable other astronomers to locate these objects. Unfortunately the coordinates listed for SS 433 were incorrect, probably because of a simple transcription error. The object could not have been found again even if another observer's curiosity had been piqued.

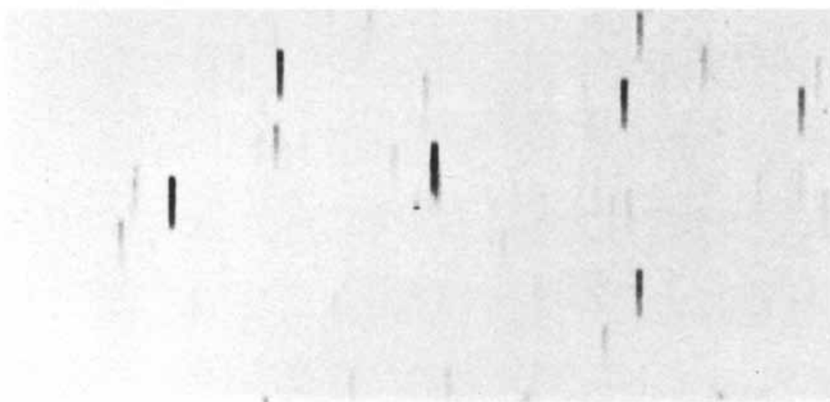
At roughly the same time as the Case survey was in progress an entirely unrelated observational program also (unwittingly) discovered SS 433. Radio astronomers at the University of Cambridge were compiling one of their several comprehensive lists of celestial radio sources, in this case the list published as the Fourth Cambridge Catalogue. Most of the sources of radio waves included in the catalogue turn out on detailed examination of optical photographs to be associated with distant extragalactic objects such as galaxies and quasars. The radio emission from normal stars in our galaxy is simply too feeble to detect in such surveys, even for objects close to the solar system. In the course of the survey a rather bright radio source was noted by the Cambridge workers in Aquila, and it was designated 4C 04.66.

If anyone at this point had noted the coincidence in the position of the radio source with the position of a fairly bright visible star, further optical observations would have almost surely been undertaken at that point, owing to the scarcity of visually detectable stellar radio sources. Again, however, the published celestial coordinates for 4C 04.66 did not agree with the actual position of SS 433. Here the probable reason for the discrepancy was instrumental; that particular region of the sky is a confused and patchy jumble of foreground and background radio sources, and the instruments used in the Cambridge survey were incapable of accurately fixing the position of even a comparatively strong source against such confusion. Once again a chance to notice the special nature of SS 433 was missed.

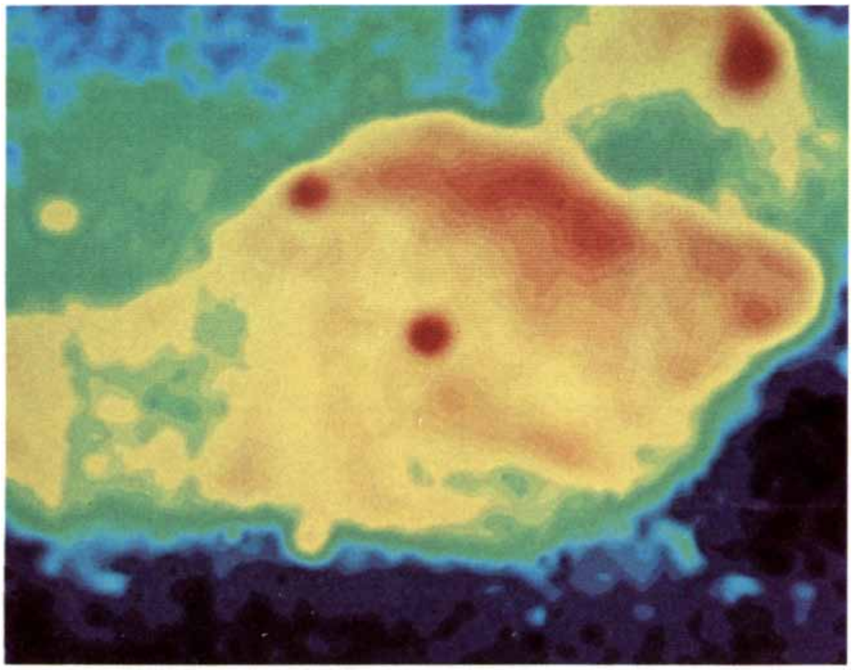
Actually part of the reason for the confusion in this case is directly relevant to the story of SS 433. Centered near that region of sky is an intense, extended patch of radio emission covering an area twice the angular size of the full moon. The radio feature is also a previously catalogued and largely forgotten object, known as W50. (The designation is derived from the source's appearance in a catalogue of radio features compiled in the 1950's by the radio astronomer Gart Westerhout of the University of Maryland.) The radio structure and radio spectrum of W50 have led most workers to suggest that it is an old supernova remnant: the diffuse, expanding remains of an ancient stellar explosion, similar to the Crab Nebula. Since there is no historical record indicating the observation of a supernova in that part of the sky, however, it has been difficult to obtain absolute proof of this assertion of the nature of W50. If indeed it is a supernova remnant, its size and radio brightness, when compared with analogous data for better-studied remnants, suggest that



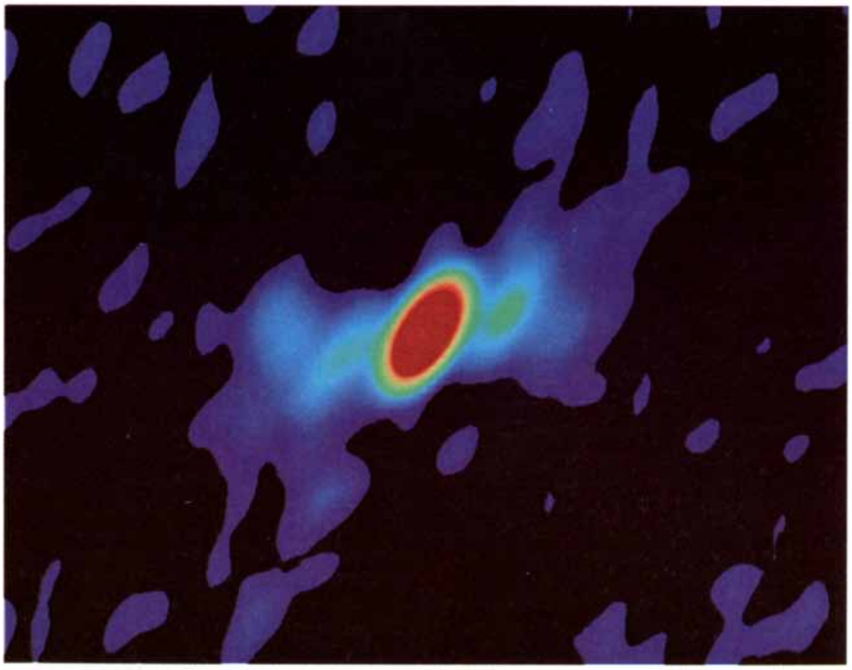
**SS 433 IS QUITE INCONSPICUOUS** in conventional astronomical photographs, such as this one made by Eugene A. Harlan with the 36-inch refracting telescope at the Lick Observatory of the University of California. The image of SS 433 is the black dot at the precise center of this circular photographic negative, which encompasses a field of view approximately a tenth of a degree across in the constellation Aquila. Classified in terms of its apparent brightness as a 14th-magnitude object, SS 433 is 1,000 times too faint to be seen with the unaided eye. The obvious lack of any visible features distinguishing the object from its many neighboring stars in this densely populated region of the Milky Way helps to explain why it was long overlooked.



**FIRST CLUE** to the unusual nature of SS 433 was discovered on this comparatively wide-field spectroscopic plate obtained more than 20 years ago in the course of a special stellar survey conducted by astronomers at the Warner and Swasey Observatory of Case-Western Reserve University. The plate was made by means of the objective-prism technique, which has the effect of smearing stellar images into short trails representing the visible spectrum of the starlight. In this case the exposure was limited by the use of appropriate filters to the red part of the spectrum, including wavelengths in the range between 6,000 and 6,800 angstrom units. In the part of the sky covered by this particular plate (an area measuring roughly half a degree across, or about the diameter of the full moon) only one spectral image shows up as a line rather than a smear; it is the inconspicuous dash near the center of the plate. Most of the red light from this object is concentrated in the extremely strong hydrogen-alpha emission line, rather than being spread continuously across all the wavelengths in this range, as in the case of the neighboring stars. In 1977 C. Bruce Stephenson and Nicholas Sanduleak of Case Western Reserve published a list of such bright emission-line objects in this part of the sky. The object at the center of the plate was the 433rd entry on the Stephenson-Sanduleak list, and hence it is designated SS 433.



**RADIO MAP of a large area surrounding SS 433 reveals that it is embedded in an extended source of radio emission, known as W50, that is believed to be the remnant of an ancient supernova explosion. The map, which covers a region of the sky approximately two degrees across, is color-coded so that red represents the most intense radio emission and blue the least intense. The bright red spot near the center coincides with SS 433. The similar spot to the northeast (*upper left*) is probably an extragalactic compact radio source, seen through the fringe of W50. The extended radio source to the northwest (*upper right*) is an unrelated cloud of ionized hydrogen between W50 and the solar system. The data for the map were recorded at a wavelength of 11 centimeters by B. J. Geldzahler, T. Pauls and C. J. Salter, working with the 100-meter radio telescope of Max Planck Institute for Radio Astronomy at Effelsberg in West Germany.**



**HIGH-RESOLUTION RADIO MAP of the area in the immediate vicinity of SS 433 was made at a wavelength of six centimeters with the Very Large Array, a complex of radio telescopes near Socorro, N.Mex. The two elongated structures emanating from the central point source in the map are aligned with the bulges in the surrounding radio source, W50. The map was produced in a collaborative study by John T. Stocke of the University of Arizona and Ernest R. Seaquist and William S. Gilmore of the University of Toronto. The color representation of the map was prepared by Eric W. Greisen of the National Radio Astronomy Observatory. The ellipticity of central source in this representation is an artifact of the imaging process.**

the explosion occurred some 10,000 years ago. Although such an age is clearly too great for the explosion to have been documented by human observers, it would still qualify the event that created W50 as one of the more recent supernovas.

A series of radio observations designed to map the detailed structure of W50 were published in 1975 by David H. Clark and his colleagues at the University of Sydney. The map also shows the bright, pointlike radio source now known to be SS 433, surrounded by the diffuse radio emission from W50. Now yet another chance occurrence intervened to inhibit further study of this curious configuration. Although the actual radio structure of W50 is quite symmetrical, with SS 433 close to the center, the map published by Clark and his colleagues showed only the northern half of the remnant, thereby somewhat downplaying the prominent central location of the mysterious pointlike source. If other observers had appreciated the striking symmetry of the remnant and therefore had recognized that the unidentified point radio source was quite precisely centered, further observation would almost surely have been stimulated.

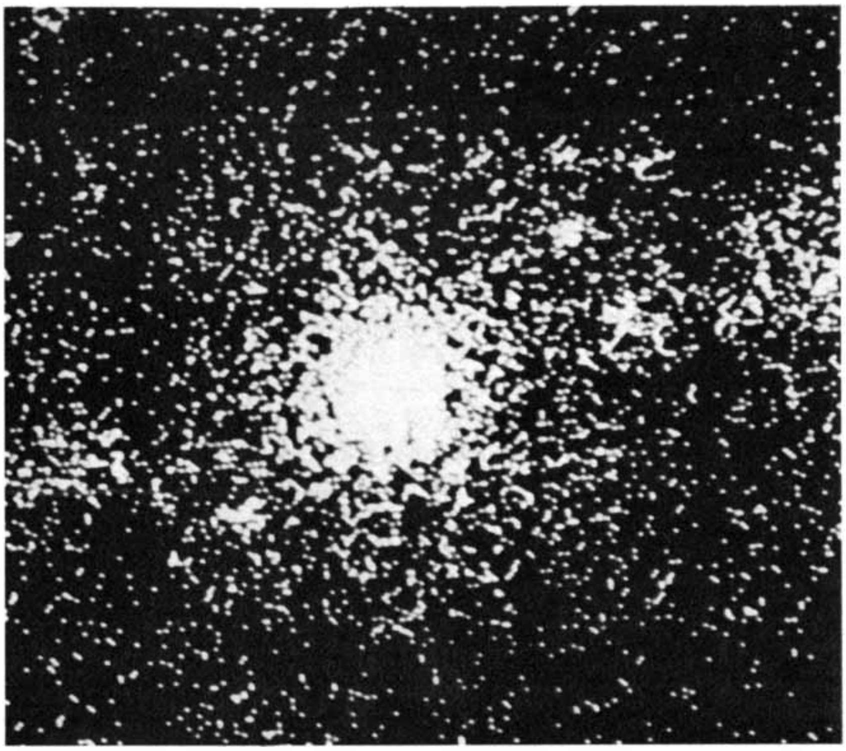
Although supernovas are widely believed to often (perhaps always) leave behind a collapsed, exotic stellar remnant such as a neutron star or a black hole, there are only two unambiguous cases where a collapsed star has actually been found in a supernova remnant. The radio and visible remnants of both the Crab event and one in the constellation Vela also harbor a pulsar, pointing to the existence of a rotating neutron star. The fact that only two such coincidences are known, in spite of the existence of dozens of radio-emitting and light-emitting supernova remnants and hundreds of radio pulsars, is annoying, although probably not profound. The opportunity to explore another potential coincidence of this type, if it had been recognized, would surely not have been missed.

The final preface to the recognition of the strange properties of SS 433 involves its X-ray emission. As is the case with radio emission, very few normal stars are a detectable source of X rays, although here again many supernova remnants are found to be X-ray sources. In the early 1970's two earth-orbiting satellites independently recorded X-ray emission from the vicinity of Aquila, and once again the source of these emissions, now known to be SS 433, was duly named and catalogued. Observers working with data from the American satellite *Uhuru* designated the X-ray source 4U1908 + 05 (from the fourth *Uhuru* catalogue, with the rough celestial coordinates of the position in the sky). Meanwhile a largely British group (led by a visiting American, Frederick D. Seward), working with data from the British satellite *Ariel V,* designated the object A1909 + 04.

The poor spatial resolution of the experiments prevented either group from perceiving the coincidence of the X-ray source and the bright star. Seward and his co-workers did note, however, that the X-ray intensity seemed to be changing with time, a characteristic not seen in the X-ray emission from supernova remnants because of their comparatively slow evolution after the initial explosion. Seward and his colleagues presciently commented in their 1976 publication that the X-ray source was probably not simply the remnant W50 but perhaps something more exotic related to it.

A synthesis of these numerous clues to the unusual characteristics of SS 433 finally emerged in the summer of 1978, as the result of the contemporaneous but largely independent efforts of three separate research groups. A group of Canadian radio astronomers led by Ernest R. Seaquist of the University of Toronto searched for emissions from young stars by conducting a new survey of objects in the Stephenson-Sanduleak catalogue. Although this led to still another rediscovery of the radio source, Seaquist and his colleagues correctly realized the source was associated with the bright stellar object SS 433. Meanwhile a group of British and Australian radio astronomers led by Sir Martin Ryle of Cambridge were tackling the quite separate problem of the observed scarcity of pointlike radio sources inside extended supernova remnants. In a sensitive survey aimed at finding and refining the positions of such objects, they again found the radio source in W50, and they also noted the coincidence with the 14th-magnitude optical object.

Finally, Clark and his colleague Paul Murdin decided to obtain spectrograms of visible stars whose position was close to the rather poorly located radio source Clark had previously noted in his map of W50. Working with the Anglo-Australian Telescope in Australia, they recorded the spectrum of SS 433 in June, 1978, the first reported spectroscopic observations since the crude objective-prism plates in the Stephenson-Sanduleak catalogue had been made. Clark and Murdin did not immediately realize that they were observing a previously catalogued object. Nevertheless, the spectrogram they obtained left little doubt that they had properly located the visible counterpart of the strange radio source. Their observations showed emission lines with an intensity found only in the most unusual stars. An extremely accurate radio position provided by Ryle's group made the identification of SS 433 with the radio source conclusive; the positions of the radio and the optical objects coincide precisely. A final, irrevocable link with the X-ray source was forged in a recent series of extremely precise X-ray measurements made by Seaquist and his group with the earth-orbiting satellite *HEAO-2,* also called the Einstein X-ray Observatory; the X-ray position is now also known to agree perfectly with the radio and optical ones.



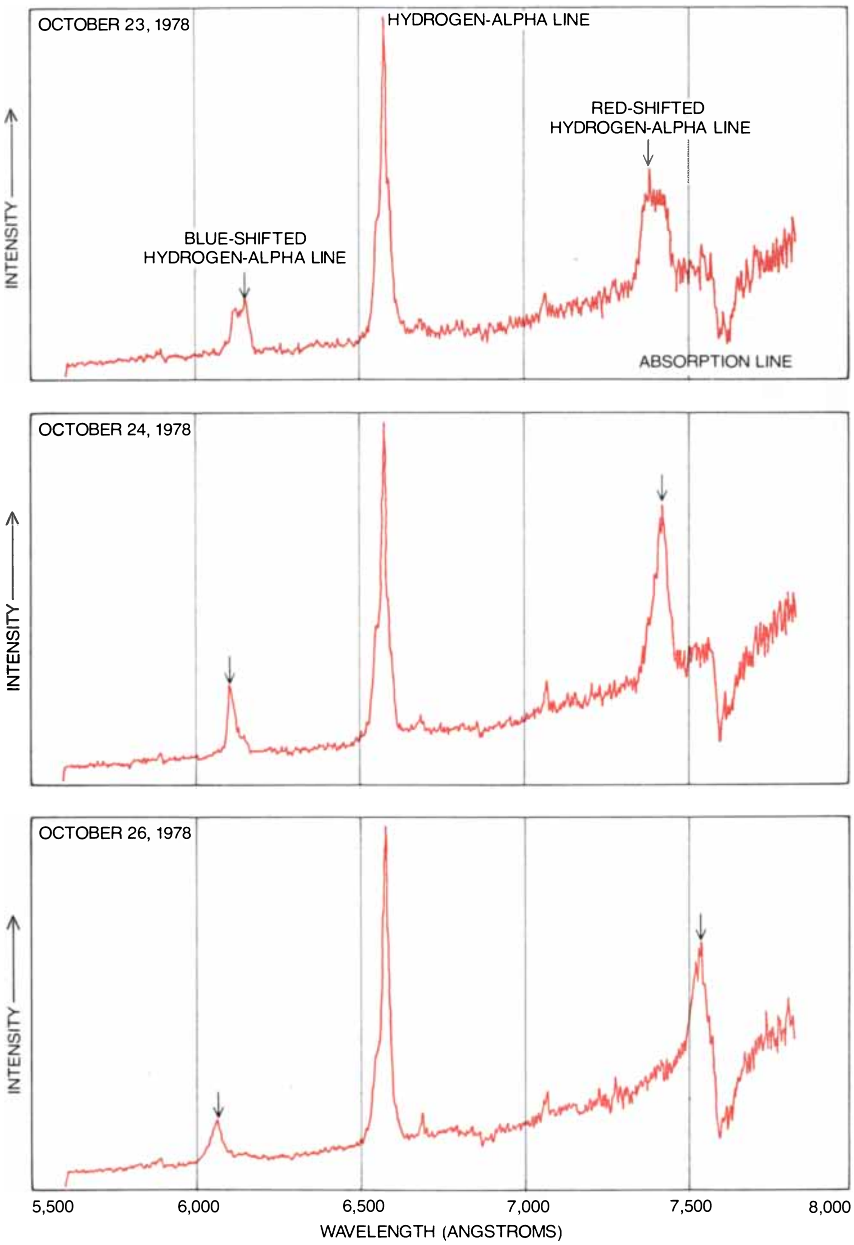
**STRONG X-RAY SOURCE coincident with the position of SS 433 appears at the center of this computer-generated picture made with data obtained by an X-ray telescope aboard the satellite *HEAO-2,* also known as the Einstein X-ray Observatory. The faint evidence of X-ray emission extending outward from the central source on both sides suggests the presence of jets of hot gas streaming toward the east and west extremities of W50. This X-ray picture, the product of an exposure of five hours, was made by Seaquist and Gilmore with Jonathan E. Grindlay and Frederick D. Seward of the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory. Field of view is approximately one degree.**

Clark and Murdin published their observations in a brief note in *Nature* in the autumn of 1978. They identified the prominent emission lines as having wavelengths appropriate for excited hydrogen and helium atoms (which was not in itself surprising, since these are invariably the most abundant chemical elements in stars). They also alluded indirectly to weaker emission lines of uncertain origin in the spectrum. (These briefly mentioned features later proved to hold the key to the entire mystery of SS 433.) Finally they stressed the striking triple coincidence of a visible emission-line star, an X-ray source and a radio source, all centered in a supernova remnant, and they suggested that SS 433 and W50 might be causally related.

At this point my own involvement with SS 433 began. I had long been interested in the optical characteristics of the faint visible counterparts of celestial X-ray sources. Most of the X-ray stars in our galaxy prove to be in binary systems consisting of a compact object such as a white dwarf or a neutron star bound in a close orbit with a comparatively normal star, often not too different from the sun. The gravitational attraction exerted by the compact star on its companion frequently causes that otherwise normal star to lose some of its mass by transferring it to the compact object. In the transfer process the streaming matter often reaches temperatures and densities sufficient to cause copious X-ray emission. Spectroscopic studies of the normal star in such systems often yield valuable data on the characteristics of both objects in them. The enormously high densities of matter in compact objects such as neutron stars cannot be attained in laboratories on the earth, and so astrophysical data provide virtually the only direct information on the behavior of matter in these exotic states.

I acquired my first spectrogram of SS 433 in September, 1978, working with the three-meter Shane telescope at the Lick Observatory of the University of California. My primary intent was simply to confirm the results of Clark and Murdin. The electronically recorded data revealed the strong emission lines of hydrogen and helium noted by those workers and also by Stephenson and Sanduleak. To my surprise, however, also present in the spectrum were very prominent emission lines not familiar to me. This was a disquieting state of affairs. Which spectral lines appear in a stellar spectrum depends on the abundance, the temperature and the density of the individual elements in the star. In astrophysical situations there is some variety in these parameters, but it is not infinite; accordingly the stellar spectroscopist gets accustomed to the appearance of certain familiar spectral lines. To encounter spectral emission lines at completely miscellaneous wavelengths is an experience somewhat akin to a driver's suddenly finding that his familiar homeward-bound freeway has all new exit ramps.

The strengths of the unidentified emission lines in the spectrum of SS 433 were particularly interesting. These lines are only slightly less prominent than the familiar hydrogen lines that also appear in the spectrum. One might therefore attribute them to a chemical element with a cosmic abundance comparable to the abundance of hydrogen. Since 90 percent of all the atoms in most stars are thought to be those of hydrogen, however, there is no such comparably abundant element. Could the unidentified lines also be due to hydrogen, and could they for some reason be displaced from the normal wavelengths seen in all other laboratory and astrophysical situations?

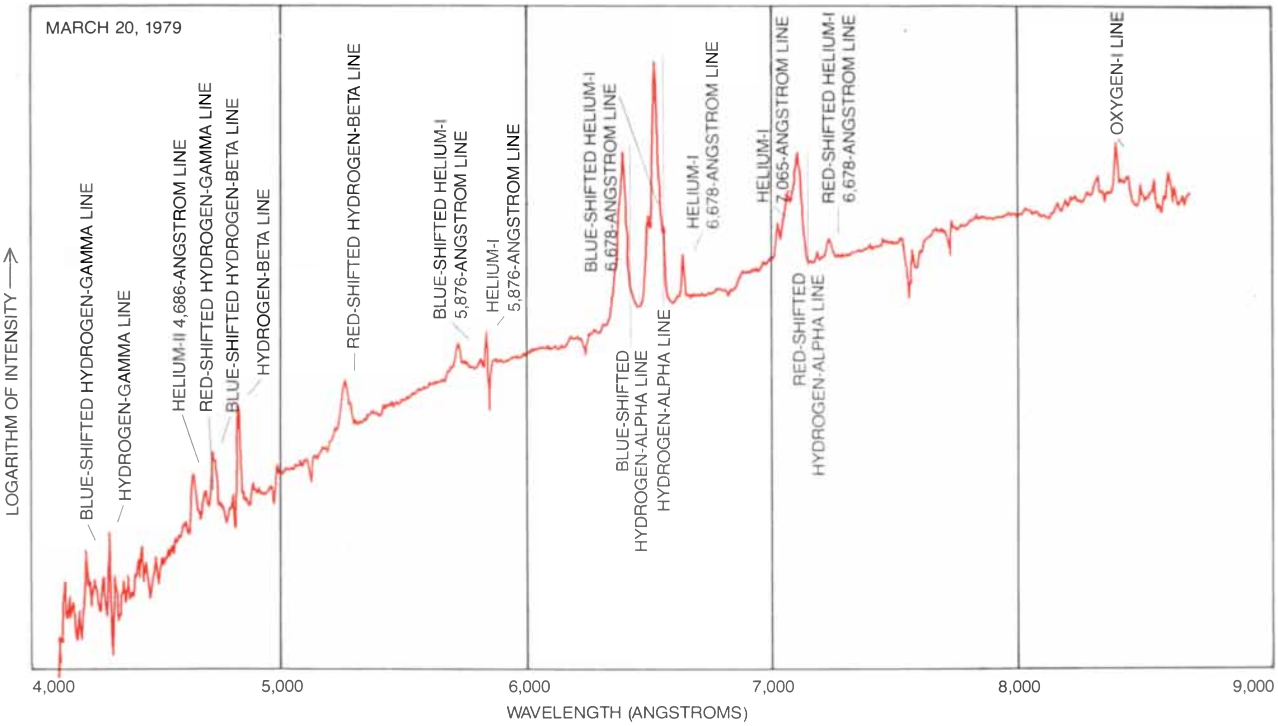



**SPECTRUM OF SS 433 was recorded on three different nights in a four-day period by Remington P. S. Stone, working with the 24-inch reflecting telescope at the Lick Observatory. The most prominent feature, the peak at a wavelength of 6,563 angstroms, corresponds to the extremely strong hydrogen-alpha emission line. Much weaker emission lines attributable to helium are detectable at 5,876, 6,678 and 7,065 angstroms. Two very strong emission features, now known to be Doppler-shifted versions of the central hydrogen-alpha line, can be seen flanking the central line, one toward the shorter-wavelength (blue) end of the spectrum (*left*) and the other toward the longer-wavelength (red) end (*right*). In the course of the three nights the red-shifted line obviously moved farther toward the red and the blue-shifted line moved farther toward the blue. The large dip in the curves near a wavelength of 7,600 angstroms is unrelated to SS 433; it is an absorption line caused by molecules in the earth's atmosphere.**

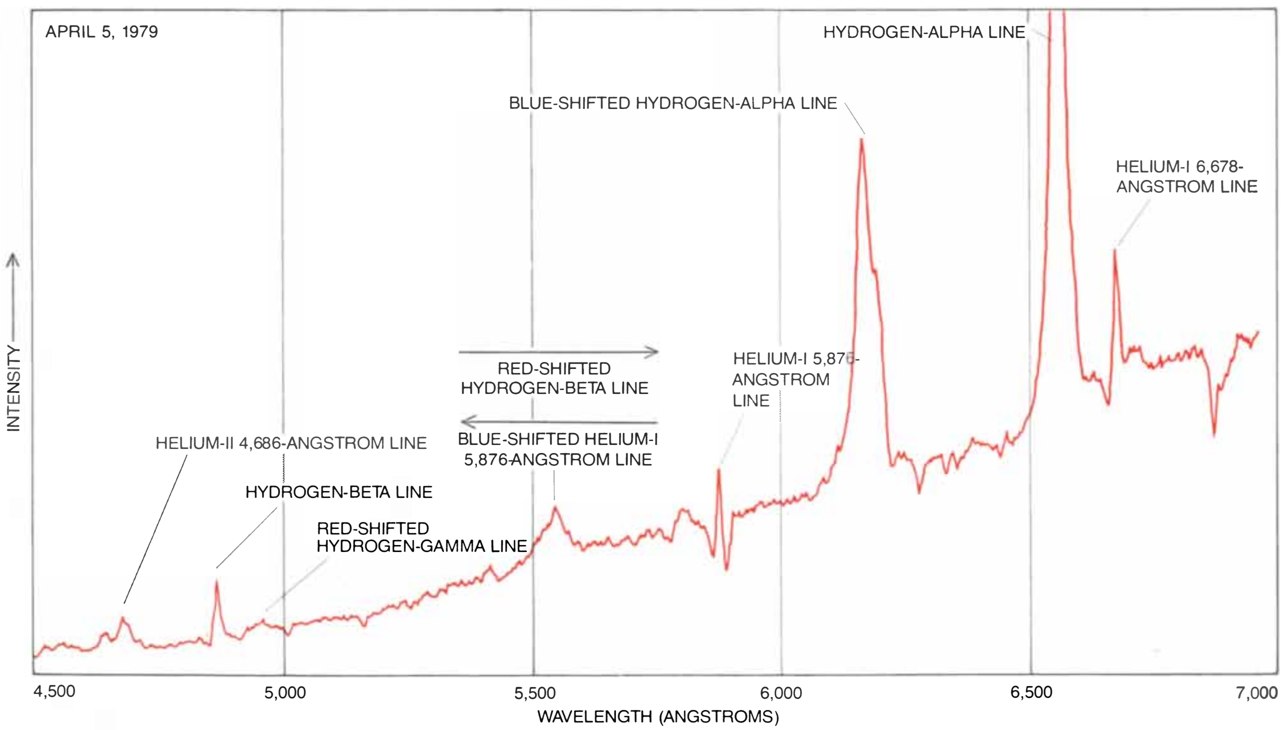
There is one such displacement mechanism familiar to the spectroscopist, namely the Doppler effect. Relative motion of the source with respect to the observer is known to slightly displace the perceived wavelength of any wave phenomenon, such as sound or light. Furthermore, the magnitude of the displacement conveniently reflects the velocity of the motion, and the sense of the displacement (toward longer or shorter wavelengths) indicates whether the object is receding or approaching. Most stars have a random motion of a few tens of kilometers per second with respect to the sun, causing a spectral-line displacement of about .01 percent from the standard values. With some binary stars the periodic orbital motion can be 10 times greater than that, causing a proportionately larger Doppler displacement.

The unidentified lines in SS 433, however, were at wavelengths not at all close to any hydrogen lines; thus if they were Doppler-displaced hydrogen emissions, the velocities implied would have to be prodigious. For the most prominent unidentified line in these spectrograms, located in the red part of the spectrum near a wavelength of 7,400 angstrom units, the velocity needed to give rise to the necessary displacement from the nearest hydrogen line (at 6,563 angstroms) is about 40,000 kilometers per second, or more than 10 percent of the speed of light! Because the escape velocity from the galaxy is only a few hundred kilometers per second stellar velocities higher than that are never encountered; any such object would quickly (on an astronomical time scale) leave the galaxy entirely. In short, Doppler-shifted hydrogen emission seemed a poor explanation of the observations.

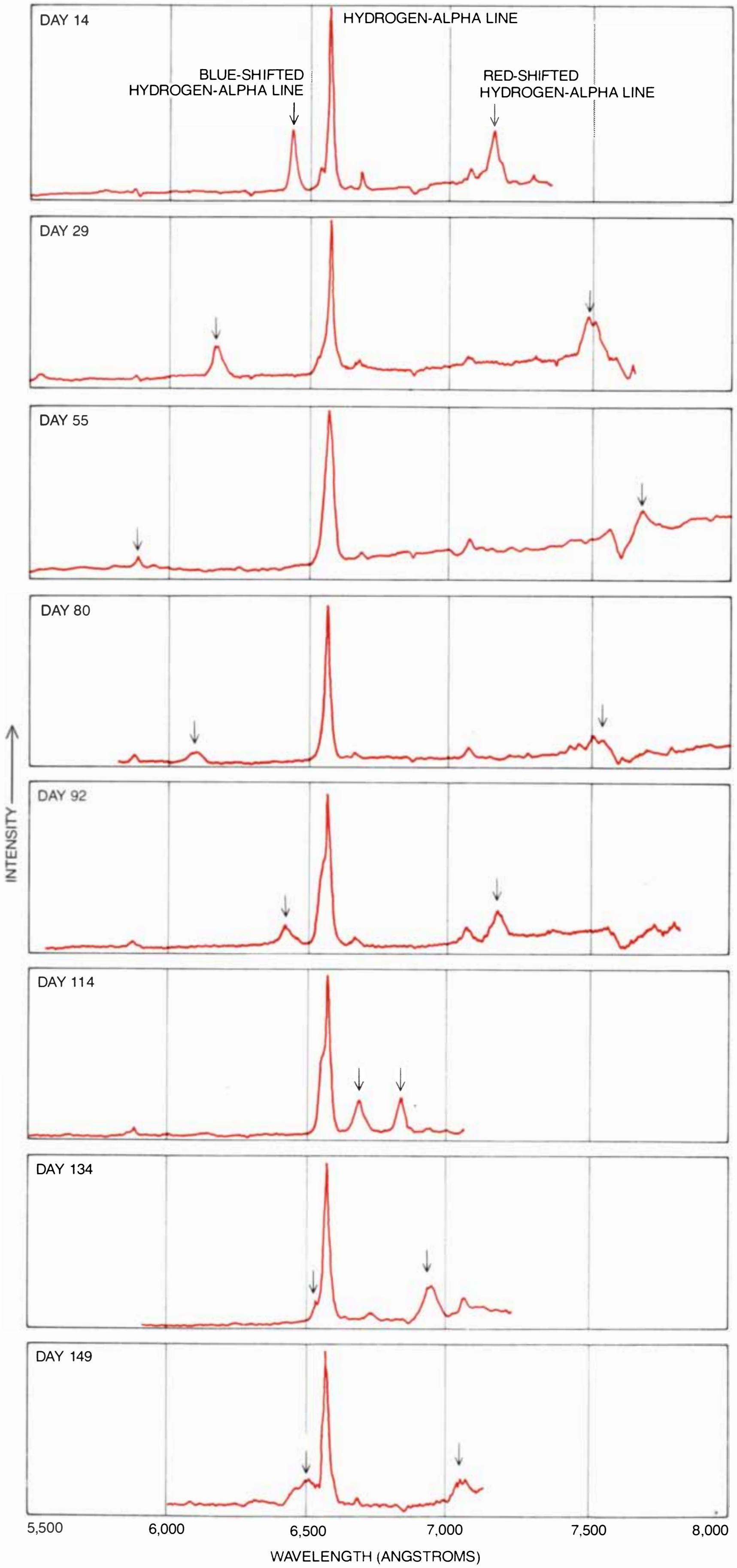
An even more bizarre characteristic of the spectrum of SS 433 became apparent after several nights of repeated study of the object. The unidentified features at unfamiliar wavelengths were seen to change wavelength, and by very substantial amounts. For example, in one four-night period the strong feature in the red part of the spectrum increased its wavelength by more than 1 percent. If the Doppler effect were responsible,




**TRIPLED EMISSION LINES** in this particular spectrogram of SS 433 are what convinced the author and his colleagues at the University of California at Los Angeles that the "moving" emission lines observed in various spectra of this object must be attributable to the Doppler effect. The spectrogram was obtained by Steven A. Grandi of U.C.L.A. on the night of March 20, 1979, with the three-meter (120-inch) Shane reflector at the Lick Observatory. A number of prominent hydrogen and helium emission lines in the spectrum are each represented three times: by a strong central component and by two flanking Doppler-shifted components, one of which is red-shifted and the other blue-shifted. The strong absorption features that appear in the spectrum are again unrelated to the stellar object.




**CONFUSING COINCIDENCE** is sometimes presented by the large number of moving Doppler-shifted emission lines found in spectra of SS 433. In this case, for example, several prominent stationary and moving emission lines are identified, among them the comparatively broad peak at the center (near 5,500 angstroms), which consists equally of a blue-shifted helium line moving to the left and a red-shifted hydrogen line moving to the right. On the night this spectrum was obtained (April 5, 1979) the two lines just happened to be passing each other in opposite directions. The spectrum was recorded at the Lick Observatory by Lawrence H. Aller and Charles D. Keyes of U.C.L.A.




this seemingly small discrepancy would need to be explained by a change in velocity of nearly 5,000 kilometers per second in those four days. Furthermore, the wavelength changes of the unidentified lines were not even consistent: some of the features moved to longer wavelengths and others simultaneously moved toward shorter wavelengths.

At this point it became clear that the spectral behavior of SS 433 was considerably more exotic than the previous observations had implied. My colleagues and I at the University of California at Los Angeles therefore initiated a program to obtain at least a brief spectral observation of SS 433 on every possible night. In spite of the severe shortage of observing time on large research telescopes, this was feasible because of the comparative brightness of the object. For example, the sensitive computer-controlled spectroscopic instrumentation of the Lick three-meter reflector is designed for the observation of very distant galaxies and quasars, objects hundreds of times fainter than SS 433. A good-quality spectrogram of this star can be had in about 10 minutes from telescopes in this class, and spectrograms can therefore be made frequently without disrupting previously planned observing programs.

Observers from all four University of California campuses where research in optical astronomy is conducted—Los Angeles, Berkeley, Santa Cruz and San Diego—participated in the observations. More than a dozen astronomers, whose primary research interests ranged from distant galaxies to nearby normal stars, generously gave of their scarce observing time to help monitor the object. Deserving of special mention are three observers who obtained as many spectrograms as I did: Steven A. Grandi and Holland C. Ford of U.C.L.A. and Remington P.S. Stone of the Lick staff.

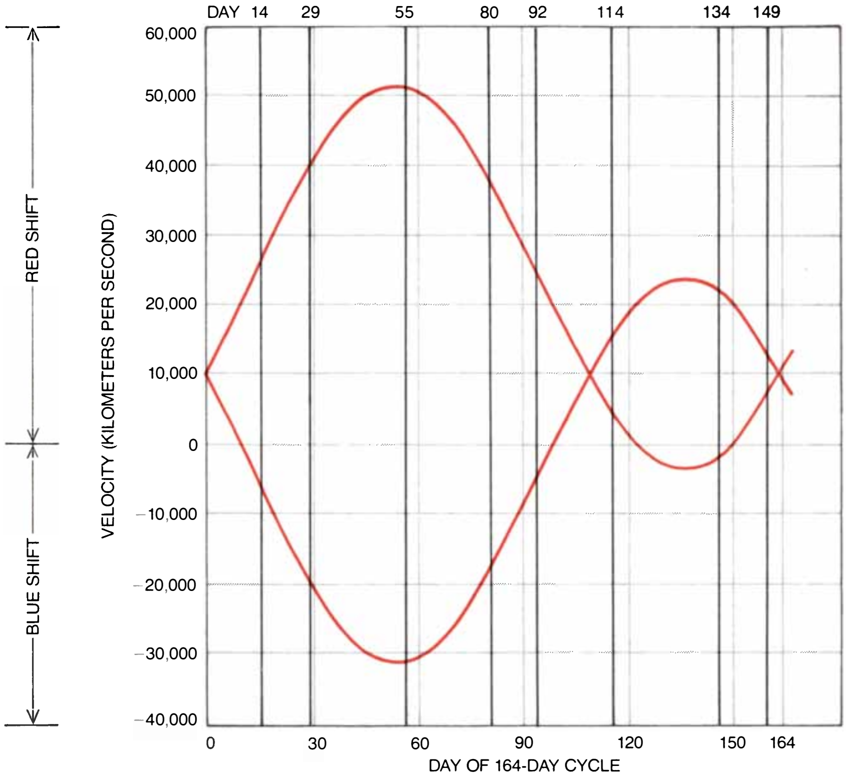
Our consortium had little time to lose, because from December through February of each year the line of sight to SS 433 is too close to the sun for nighttime observations. By the end of the 1978 observing season we had watched the "moving" spectral lines, as we came to call them, traverse a staggering range of wavelengths. For example, the reddest emission feature changed its wavelength by about 700 angstroms in 30 days, which, if it was interpreted as a gradually increasing Doppler shift, would im-

**SELECTED SPECTRA of SS 433, obtained by the author and his colleagues over a period of 164 days, cover the entire cycle of the motion of the Doppler-shifted emission lines. The days the observations were made are given in relation to a model of the 164-day cycle in the illustration on the opposite page.**

ply a steady increase in velocity from 20,000 kilometers per second to 50,000.

In our initial reports of the data to the scientific community we tried to remain skeptical about the Doppler-shift interpretation of the moving lines for a variety of reasons that all seemed valid at the time. The most obvious objections were those I have already mentioned. Both the velocities implied and the changes in the velocities were larger by a factor of 100 than comparable values found in any other stellar object. There were also subtler difficulties with the Doppler-shift explanation. Some of the moving lines shifted toward longer wavelengths and others shifted toward shorter ones, defying the simple interpretation of a single cloud of gas either approaching or receding.

Furthermore, the identification of the moving emission lines as Doppler-shifted hydrogen lines would imply the existence of a gas at a rather modest temperature, about 20,000 degrees Kelvin or less; at temperatures higher than that most of the hydrogen would be ionized, and spectral lines due to the transitions of an electron bound to an atomic nucleus could not appear. Yet almost any mechanism one can imagine that could accelerate a gas to the enormous velocities implied (a substantial fraction of the speed of light) would heat the gas to a far higher temperature. Another way to put this difficulty is to note that if the thermal and the kinetic energy of the hydrogen nuclei in the emitting gas are roughly equal, as is often the case in a variety of physical systems, the observed velocities imply temperatures of more than 30 billion degrees K., far higher than the temperature inferred for the gas observed in SS 433.




**THEORETICAL CURVES trace out one complete 164-day cycle in the predicted pattern of red-shifted and blue-shifted spectral emission lines for SS 433, on the assumption that the light-emitting gas is concentrated in two oppositely directed rotating jets, each with an ejection velocity of 78,000 kilometers per second, or about a fourth the speed of light. The black lines indicate the days on which the selected spectra that appear on the opposite page were obtained. The emission features in the spectra match the predicted red shifts and blue shifts quite closely. The curves exhibit a constant average red shift equivalent to an ejection velocity of 12,000 kilometers per second, which results from the effect of special relativity called time dilation.**

Our concerns did not inhibit a host of imaginative theorists. Andrew Fabian and Martin Rees of Cambridge pointed out that the existence of a gas Doppler-shifted in both directions could be understood if a central object were ejecting two jets of gas in roughly opposite directions. Then some gas would be approaching the observer and other gas would be receding. Fabian and Rees noted the existence of similar double-lobed structures seen on a vastly larger scale in radio galaxies, where the radio emission is often found to be confined to two opposed jets. A similar scheme was proposed independently by Mordechai Milgrom of the Weizmann Institute of Science in Israel, who went even further to make a guess that later proved to be spectacularly successful. On the basis of only a handful of our data points Milgrom speculated that the line motions might be periodic, with a repetition time of about a few months.

Meanwhile we continued to worry about the entire basic idea. Were the unidentified moving emission lines actually Doppler-shifted hydrogen lines? The answer became apparent in March of last year, when SS 433 was again far enough from the sun for spectroscopy. Our first spectrogram of the new observing season clearly showed all of the principal emission lines to be tripled: one component at the laboratory (undisplaced) wavelength, one at a wavelength displaced toward the red end of the spectrum (toward the longer wavelengths) and one displaced toward the blue end (toward the shorter wavelengths). Both hydrogen and helium emission lines, about half a dozen different features in all, exhibited this peculiar triple pattern. Furthermore, each of the red-shifted lines independently implied an identical velocity of recession, about 27,000 kilometers per second, and each of the blue-shifted features similarly implied an identical velocity of approach, about 6,000 kilometers per second. This multiple set of coincidences could be explained only by the Doppler shift. A similar conclusion was reached independently at about the same time by a group of astronomers at the University of Arizona directed by James W. Liebert.

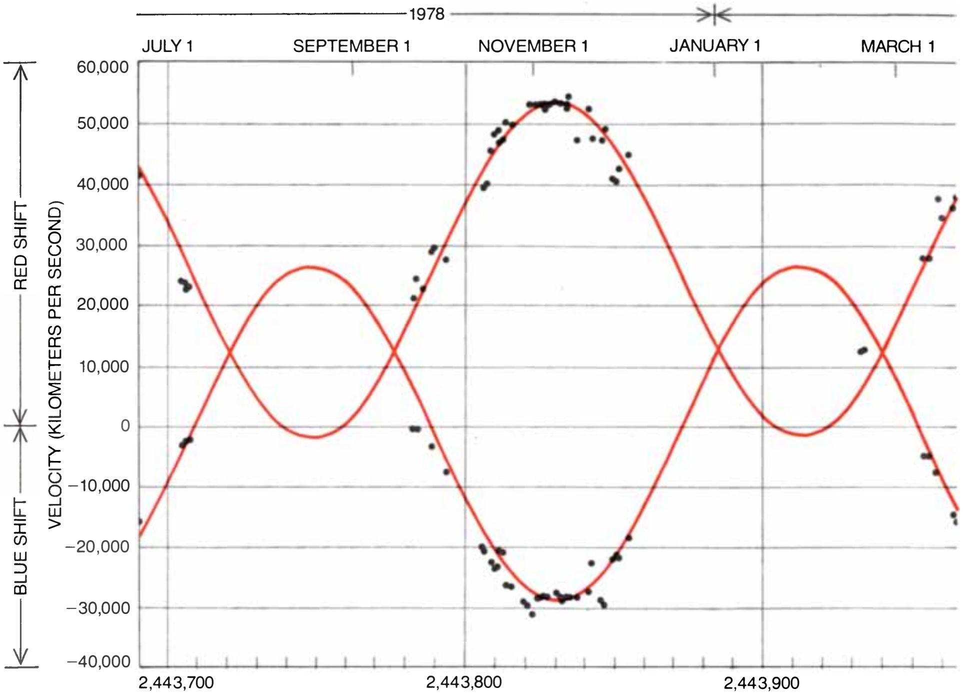
In a curious way the difficulty in interpreting the moving lines in SS 433 was an eerie repetition of the sudden recognition of the meaning of quasar spectra by Maarten Schmidt two decades ago. The huge red shifts of the quasars, caused by the expansion of the universe, also displaced the emission lines so much from their normal wavelengths that it was hard to identify the atoms that gave rise to them, in spite of the fact that the lines turned out to be associated with the most abundant and familiar elements in the universe. Even though the history of the discovery of quasars was well known to all of us, SS 433 presented an initial interpretive problem because of two unprecedented complications: first, such enormous red shifts had never been associated with stars within our galaxy, and second, the object was evidently showing blue shifts as well as red shifts.

It is clear that since the wavelength of the Doppler-shifted features changes rapidly with time, the velocity of both the approaching gas and the receding gas is changing. An obvious question then is: Is there any regular pattern to these changes? In our two years of observations we have accumulated some 150 separate measurements of both red-shifted and blue-shifted emission lines; a graph of the values of the implied velocities as a function of time reveals several fascinating features in the strange behavior of the moving lines [*see illustration on these two pages*]. One sees immediately that the velocities are truly enormous: the red-shifted (receding) gas reaches values up to 50,000 kilometers per second (16 percent of the speed of light) on several different occasions, and the blue-shifted (approaching) gas reaches velocities of up to 30,000 kilometers per second. Because the velocities of stars in our galaxy (either approaching or receding) never exceed a few hundred kilometers per second, and because all extragalactic objects beyond the immediate vicinity of our galaxy show only red shifts, attributable to the expansion of the universe, SS 433 has the distinction of exhibiting the largest blue shift (by a factor of 100) of any known celestial object, galactic or extragalactic.

More pieces of the puzzle fell into place after an analysis of the pattern of velocity changes. The approaching and receding volumes of radiating gas are certainly not coincident in space; if they were, they would separate rapidly at these enormous oppositely directed velocities. Yet in spite of their physical separation the two clouds of gas are definitely related; the variations in the red-shifted and blue-shifted systems reach their extremes of velocity at identical times. Moreover, the average value of the two velocities on any given night is roughly constant but very large: about 12,000 kilometers per second.

The constancy of the mean of the two Doppler-shifted velocities, in spite of the huge change in their individual values on a time scale of days, could perhaps be understood if one central object were responsible for ejecting both radiating clouds; the average velocity would then be that of the central star. Once again, however, we were confronted with the problem that this value exceeds by a wide margin the escape velocity from our galaxy; the object would depart from the galaxy forever in a tiny fraction of the age of the stars in the neighborhood of the sun (at least 10 billion years). Is it reasonable to believe that one just happens to be alive and doing astronomy during this brief interval? As it turns out, a considerably less strained explanation is available.

I have yet to address perhaps the most startling characteristic of the variation in the velocities of the material associated with SS 433. In spite of the large and continuous variations in velocity, and the considerable gaps in the observations, it can be seen from an examination of the illustration on these two pages that both the red-shifted gas and the blue-shifted gas repeatedly return to the same velocity values approximately once every six months; in other words, the variations in velocity are periodic. A simple analysis of the current data shows the exact period to be 164 days, with an uncertainty of about half a day. The pattern of the variations is quite distinctive. Twice each 164 days the two emitting systems merge to the identical velocity and then change places, that is, the blue-shifted gas becomes red-shifted and vice versa. Observationally these events are seen in the spectrum as a gradual merging of the moving lines, which then pass through each other, drawing apart in opposite directions. We have observed this "crossover" event several times, although we have not yet been lucky enough to obtain a spectrogram during the precise (presumably brief) interval when the moving lines are exactly superposed.

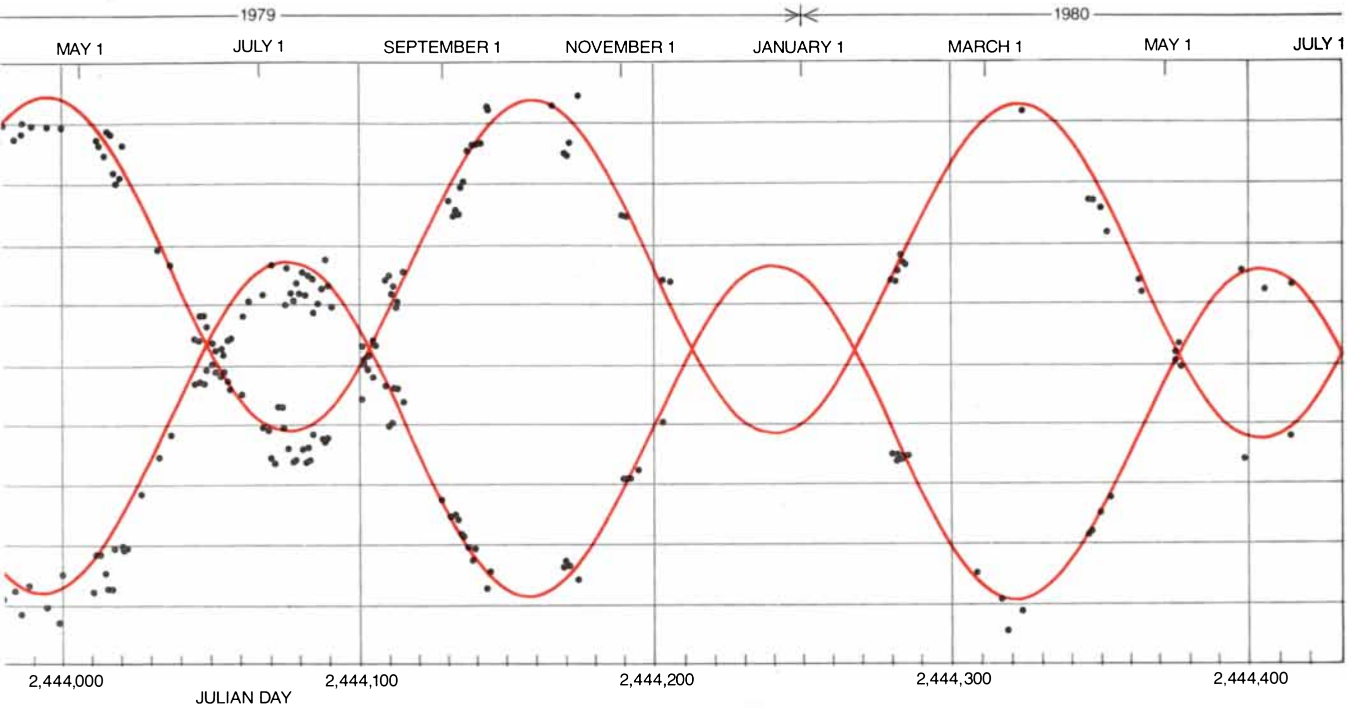



**TWO YEARS OF OBSERVATIONS are summarized in this illustration, which plots the values of the red- and blue-shifted emission lines observed in the spectrum of SS 433 from mid-1978 to mid-1980 in terms of the equivalent velocity of the ejected gas. The large gaps in the**

There is a familiar precedent for this type of periodic spectral variability, albeit one on a greatly reduced scale. In certain binary star systems if the brightness of the two stars is comparable, two independent sets of spectral lines are sometimes visible. Because at any instant one star has some component of velocity toward the solar system and the other star has some component of velocity away from it, the Doppler shifts of the same spectral line in each star are slightly different; hence the lines appear as a resolvable pair at slightly different wavelengths. As the two stars revolve around their common center of mass the component of motion of each star toward or away from the earth changes smoothly and periodically; accordingly the wavelengths of each of the two spectral lines evince a periodic change between a short-wavelength limit and a long-wavelength one. In binary star systems, however, the amplitude of the change in velocity never exceeds a few hundred kilometers per second, whereas in SS 433 the amplitude is more than 100 times greater.

Could SS 433 represent some enormously scaled-up version of this phenomenon, consisting simply of two mutually orbiting objects? If this were the case, there would be a fascinating consequence. One corollary of the simplicity of the gravitational force is that all orbiting bodies, regardless of their nature, obey a basic relation between the orbital period, the orbital velocity and the total mass in the system. Therefore if one assumes that the dramatic wavelength variations of SS 433 are due to orbital motion, then with only the observed amplitude and period of the variation in velocity the total amount of matter in SS 433 can be directly calculated. The result is a total mass equivalent to a billion times the mass of the sun! Since the most massive stars known have a mass of less than 100 solar masses, this result is startling. In fact, the mass inferred in this way for SS 433 is about 1 percent of the total mass of the 100 billion stars in the entire galaxy.

Is it credible that an object with such an extraordinary mass has been overlooked until now? The answer is no. There are several different arguments that can be relied on to show that the strange spectral-line variations cannot be due to orbital motion. For example,




**data are correlated with times when the line of sight to the object was too close to the sun for nighttime observation; the smaller gaps are attributable to the proximity of the moon, which makes observing difficult, or to the lack of observing time on a suitable telescope. Curves show the predicted behavior, based on the assumption that the gas responsible for Doppler-shifted lines is in two oppositely directed jets.**

the putative orbital parameters are such that the diameter of the orbit would be so large that it would take light some two weeks to travel between the orbiting objects. Yet the peaks and valleys in the plot of the system's red shifts and blue shifts remain synchronized with each other to an accuracy of within a day or so. According to the special theory of relativity no information, regardless of its method of transmission, can propagate faster than the speed of light. Therefore it would be impossible for the two objects to remain synchronized; they cannot, so to speak, "tell" each other where they are.

A second item of evidence arguing strongly against orbital motion is the stationary emission system in the SS 433 spectrum, that is, the set of spectral lines that are constantly close to their laboratory wavelengths. If the gas emitting these lines were in the vicinity of an object with a mass of a billion solar masses, it would rapidly feel this enormous gravitational attraction and fall in toward the larger mass. Yet the velocities indicated by these lines are quite small.

For all of these reasons, together with subtler arguments, it is not feasible to invoke two mutually orbiting bodies to explain the rapid wavelength changes in the spectrum of SS 433. Most of the workers interested in the problem have turned instead to modifications of the concept in which one central object ejects two jets of matter, one jet directed approximately toward the earth, thereby giving rise to blue-shifted emission-line radiation, and one jet directed approximately away from the earth, thereby giving rise to red-shifted radiation. If in addition it is postulated that the imaginary line joining the two jets rotates at a rate such that a complete turn is made every 164 days, the periodic modulations of the observed velocity values are also explained. That is because at each point in the 164-day cycle the angle of each jet with respect to the line of sight to the earth varies. When the jets are closest to pointing directly toward (or away from) the earth, the largest velocities of approach (and recession) will be observed. On the other hand, when the jets are directed across the line of sight, there is no gas moving either toward or away from the earth, and one would expect the velocities to be at a minimum.

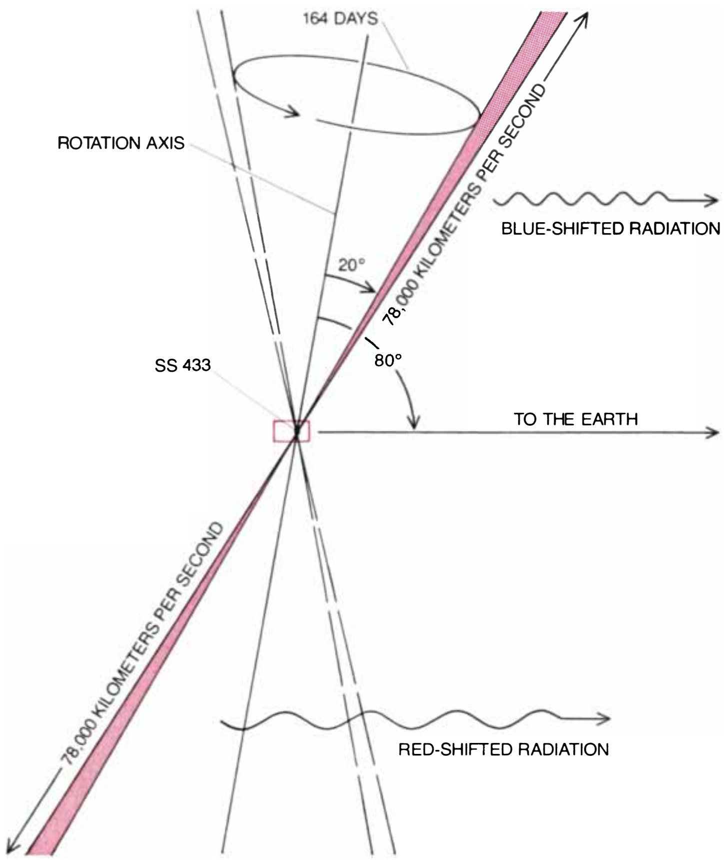
It is easy to quantify this idea with a simple set of equations. Surprisingly there are only five unknowns in the equations; in other words, five characteristic parameters should be enough to completely describe the behavior of the object. To begin with there are two unknown geometric angles. One is the inclination of the axis of rotation of the object to the line of sight. For example, an extraterrestrial observer able to perceive the earth's rotation would not necessarily have to be stationed exactly above the Equator; he would see the rotation from any latitude. We do not know the "latitude" from which we are observing SS 433. The second unknown angle is the inclination of the axis of the jets to the rotation axis. Our angle with respect to the jets need not be the same as this first angle, just as the axes of the earth's geographic and magnetic poles are slightly inclined with respect to each other. A third unknown is the velocity with which the jets are ejected; for the sake of simplicity it is convenient to assume that the two jets are ejected in opposite directions but with the same speed. (If this assumption is wrong, there is no solution to the equations.) Finally, the precise values of the period and the phase of the 164-day cycle of SS 433 are both unknowns that must be determined from the data.

Our spectroscopic observations can be fitted to this theoretical model to determine if any values of the five parameters can be found that seem to agree with the data. It turns out that this simple concept, perhaps surprisingly, fits the data quite well. The two angles prove to be respectively about 80 and 20 degrees, and the jet velocity implied by the observations is 78,000 kilometers per second, or 26 percent of the speed of light. The reason we never directly observe a red shift or a blue shift quite as large as this value is simply that the two geometric angles turn out not to be right angles. Thus the jets do not point directly toward or away from the earth. (Indeed, it would be suspicious if they did.) The maximum velocity component of the gas moving toward or away from the earth therefore cannot reach the actual velocity inferred for the jets. An observer fortuitously located along the projected path of the jets would see this maximum and minimum velocity.

For matter moving at a significant fraction of the speed of light, effects predicted by the special theory of relativity become important. In fact, it is just such an effect that explains one of the more puzzling aspects of SS 433: the very large and constant average velocity (12,000 kilometers per second) of the two jets. The relevant effect has several different technical names, such as the second-order or transverse Doppler shift, but it is often referred to simply as time dilation. An imaginary observer watching someone moving at high velocity and carrying a clock would perceive the clock to be running slow; the higher the velocity, the slower the clock. The person carrying the clock, on the other hand, would perceive the clock to be keeping perfect time. Indeed, since all motion is relative, he might accuse the "stationary" observer of faulty time perception.

What does this have to do with SS 433? Each atom in the ejected gas has the equivalent of a clock, since it must keep track of the frequency (or equivalently of the wavelength) in order to emit light at the proper wavelength whenever its electrons are de-excited. Since time dilation always slows the clock, and since the frequency and the wavelength of light are inversely proportional, the decrease in frequency will appear as an increase in wavelength, in other words as a red shift. The amount of the time-dilation red shift depends only on the velocity of the clock, and it is easy to calculate that at a velocity of about a quarter of the speed of light the effect of time dilation is 4 percent.

This may seem a small discrepancy, but remember that a red shift of 4 percent of the speed of light (300,000 kilometers per second) is 12,000 kilometers per second. This, of course, is exactly the observed average value of the two beams of SS 433. The time-dilation red shift is always present in the jets, regardless of their angle with respect to the line of sight. Therefore the 164-day, periodically varying Doppler shift is superposed on (adds to and subtracts from) the time-dilation red shift. This interpretation nicely explains not only why 12,000 kilometers per second is the average velocity actually observed but also why the emission lines associated with the two jets merge twice every 164 days at that large value rather than at zero velocity. The crossover events occur when the two jets are pointing at right angles to the line of sight. Even though at those times there is no approach or recession of the emitting gas, and thus no red shift or blue shift other than the time-dilation one, the ever present effect of time dilation gives both beams a red shift equivalent to 12,000 kilometers per second.




**GEOMETRY OF THE ROTATING-JET MODEL of SS 433 is laid out in this schematic diagram. The rotation axis of the object is inclined to the line of sight to the solar system by an angle of about 80 degrees. The jets themselves are in turn inclined by about 20 degrees to the rotation axis. The period of the rotation is 164 days. The velocity of the jets works out in this model to be about 78,000 kilometers per second. The component of this velocity projected along the line of sight varies periodically as the axis of the jets rotates; hence the Doppler-shifted emission lines in the spectrum of the object fluctuate between maximum and minimum positions, depending on the inclination of the jets to the line of sight. In the position shown here, for example, both the red shifts and the blue shifts would be at a maximum; minimum red shifts and blue shifts would be observed when the jets are at right angles to the line of sight.**

What is the mysterious central object that emits the jets? It is hard to say, but we do have one important clue, namely the observed velocity: 26 percent of the speed of light. Why is it that value and not some other one? The answer may be that that velocity is quite close to the escape velocity of matter from the surface of a neutron star. Theoretical calculations show that there is a limited range of parameters over which these exotic stars can support their own mass and thus be stable. A neutron star with a mass equal to that of the sun would have a radius of only about 10 kilometers. The velocity needed to escape from the surface of a neutron star turns out to be similar to the one observed in the jets of SS 433. Perhaps this is a coincidence, but if it is not, it suggests the possibility of a self-regulating mechanism of expulsion. The gas may be accelerated up to whatever velocity is necessary to expel it permanently; then the acceleration mechanism, having done its job, need work no harder. One can also reverse the argument. If the star is not that compact, why should it generate and maintain the observed enormous expulsion velocity, if instead it could economically be rid of the material forever by imparting to it a much lower velocity?

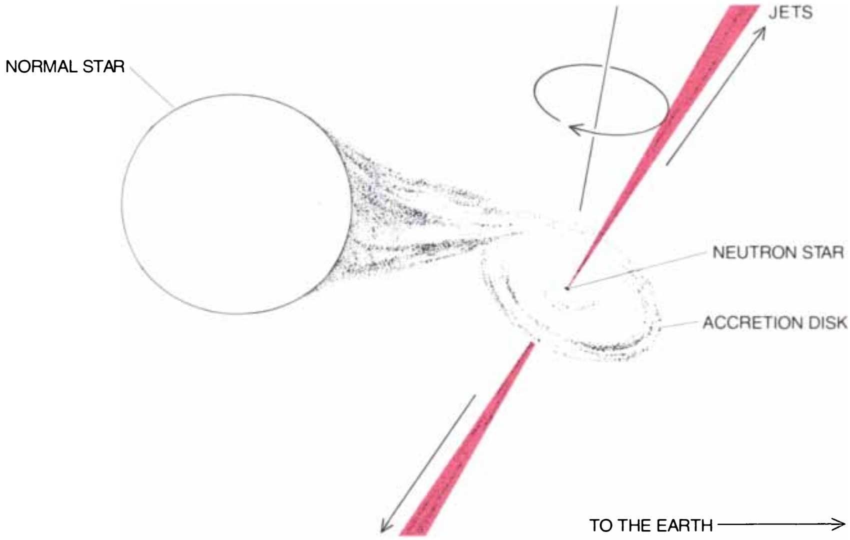
If SS 433 does harbor a neutron star, the 164-day clock (that is, the mechanism that rotates the jet axis) is probably not simply the rotation of the star every 164 days. That is because the very small size of the star implies that at that low rate of rotation the object is not very stiff. (Technically one would say that its moment of inertia is not very large.) On the other hand, the ejected material carries away a tremendous amount of energy at a fantastic velocity. The resulting recoil given to the star would very quickly disrupt the periodic behavior unless the two masses of ejected material are exactly matched in velocity and alignment, so that their effects on the star perfectly cancel each other. It seems more likely that the 164-day period is instead a precession effect, a slow wobble of the rotation axis. The actual rotation period of the star could then be rapid, as it is with radio pulsars, where the periods are on the order of a few seconds or less. An apt analogue is a toy gyroscope, whose wheel can spin very rapidly while the entire assembly turns slowly in a circle.

What is the source of the ejected material? Since the emission lines are from hydrogen and helium, elements typically found in objects far less evolved than neutron stars, the material probably does not come from such a star. The interstellar medium is largely composed of hydrogen and helium, but it is far too tenuous to supply enough gas. One is therefore led to suspect the presence of a second, less evolved star.

This line of thought led David Crampton, Anne P. Cowley and John B. Hutchings of the Dominion Astrophysical Observatory in Canada to obtain a series of spectrograms of SS 433 that might be sensitive to such a companion star. They soon discovered that the "stationary" emission lines, the emissions of hydrogen and helium at their laboratory wavelengths, are also cyclically shifting in their wavelength. The amplitude of the shift is very small, corresponding to 70 kilometers per second (about .1 percent of the amplitude of the shift of the moving lines), and therefore it could not be detected by the equipment my colleagues and I were using for our observations. The period of the minor variation is 13 days. Again the observed period and amplitude of the velocity variation lead to estimates of the masses of the two stars. A consistent, although not unique, solution is obtained if both stars are assumed to have a mass comparable to that of the sun. The parameters of the orbital solution suggest that the companion of the neutron star is probably a normal star, with characteristics not very different from those of the sun. Unfortunately such an object would be too faint against the background of the radiation from the jets to be observed directly.

Lest it seem that all the mysteries of SS 433 are now understood, I should review the host of perplexing problems remaining to be solved. Most of them center around the physical conditions in the ejected material. It is possible to calculate some of the parameters in the emitting gas; to do so, however, one must make some guess at the distance of SS 433, so that the observed intensity of the jets' radiation can be used to calculate the intrinsic luminosity. Like most estimates of astronomical distances, this one is grossly uncertain. On the basis of arguments such as the strength of spectral absorptions due to the intervening interstellar gas, I estimate the distance to be about 4,000 parsecs. (One parsec is 3.258 light-years.) Our galaxy is about 30,000 parsecs across, and so SS 433, although not an immediate neighbor of the sun, is not extremely distant.

It is now possible to calculate the luminosity of the jets. The few moving emission lines prove to have more energy, by about a factor of 10, than the sun radiates at all wavelengths. The length of the visibly radiating material is about 10 billion kilometers, that is, about 100 times the distance from the earth to the sun, or twice the size of the entire solar system. The most startling parameter, however, is the amount of kinetic energy inferred to be necessary to accelerate the considerable mass of material to the extraordinary velocity observed. Although the figure depends somewhat on uncertain assumptions, it is on the order of $10^{39}$ ergs per second, or a million times the energy radiated at all wavelengths every second by the sun. What is the source of this fantastic energy output? We are not at all certain.




**HYPOTHETICAL CENTRAL OBJECTS postulated by the author and his colleagues to help explain the observed characteristics of the spectrum of SS 433 according to the rotating-jet model are depicted in this diagram, which can be seen as an enlargement of the area inside the small colored box in the illustration on the opposite page. The object responsible for ejecting the jets is thought to be part of a binary star system, consisting of a comparatively normal star (*left*), not unlike the sun, bound in a close orbit with a compact neutron star (*right*), which is in the process of pulling material away from its normal companion by virtue of its strong gravitational field. (Both stars are assumed to be about as massive as the sun.) The gas streaming from the normal star forms a rotating accretion disk around the neutron star, and it is from the faces of this disk that the two jets are ejected in opposite directions. Precession of the plane of the accretion disk around the neutron star is presumably what causes the axis of the jets to rotate.**

The more detailed questions we ask about the jets, the more our ignorance is revealed. What mechanism harnesses this energy to accelerate the gas, yielding just one accurately controlled and unchanging velocity? Why is the gas so cool compared with the temperatures expected at these velocities? What process collimates and directs the material into a jet? The last question is particularly vexing. We now have an observational measure of the width of the jets based on the width of the moving spectral lines. If the jets were broad, at any given instant such a wide swath would present a variety of angles as well as different velocities and different Doppler shifts. We would then expect the moving lines to be broad, spanning this range of Doppler velocities. Actually we observe the opposite: the moving lines are quite narrow compared with the huge velocity of the jets. The inference is that the jets are less than a few degrees wide, almost like two sharp needles.

Finally, and perhaps most intriguing, is the question: Where are the other objects like SS 433? Why do we observe only one such object in a galaxy of 100 billion stars? A possible answer is that the lifetime of this bizarre event may be very short by astronomical standards, perhaps only on the order of 10,000 years. Many stars may pass through this phase but only for an astronomical instant. There may be only one such object active at any one time.

It is surely foolish to speculate what might be said about the general significance of SS 433 to astrophysics five or 10 years from now. Nevertheless, it is intriguing to guess. The most interesting possibility is that the resemblance of the twin-jet structure of SS 433 to the double-lobed radio emission from giant galaxies and quasars is not a coincidence. If the same basic mechanism underlies both phenomena, and if the answers to the above questions of energetics, acceleration and collimation are related in both, it would be tremendously exciting. We would then be privileged to have a revealing closeup view of a comparatively nearby object within the galaxy that could serve as a prototype for gaining an understanding of the violent extragalactic events that are among the greatest mysteries in astronomy.