A Star that has Risen from the Dead

by
Sun Kwok

One night in September 1976, three Russian astronomers at the Piszkesteto Observatory in Hungary noticed a new star in the constellation Sagitta. A search through old photographic plates at the Sternberg State Astronomical Institute of Moscow University showed that the star was invisible — fainter than the magnitude limit of the plates — prior to April 1976. Then, between April and September 1975, its brightness rose by a factor of 40, from 16th magnitude to about 11th magnitude. As a result, O. Dokuchaeva of Moscow University issued a bulletin to alert international variable star observers. One of the most remarkable stars in the history of variable star research had just been discovered.

A search through the archives of photographic plates at the Harvard and Sonneberg Observatories confirmed the existence of a "new" star. But while a classical nova usually fades from its visual maximum after a few days, this star seemed to remain fixed at maximum light. In March 1977 it was officially given the variable star name HM Sagittae.

Shortly after its discovery, Richard Stover and Svein Siverstsen of the University of Texas obtained the star's spectrum. Surprisingly, its spectrum did not resemble that of a nova — it was full of bright atomic emission lines, which normally characterize planetary nebulae. Its nature totally perplexed astronomers.

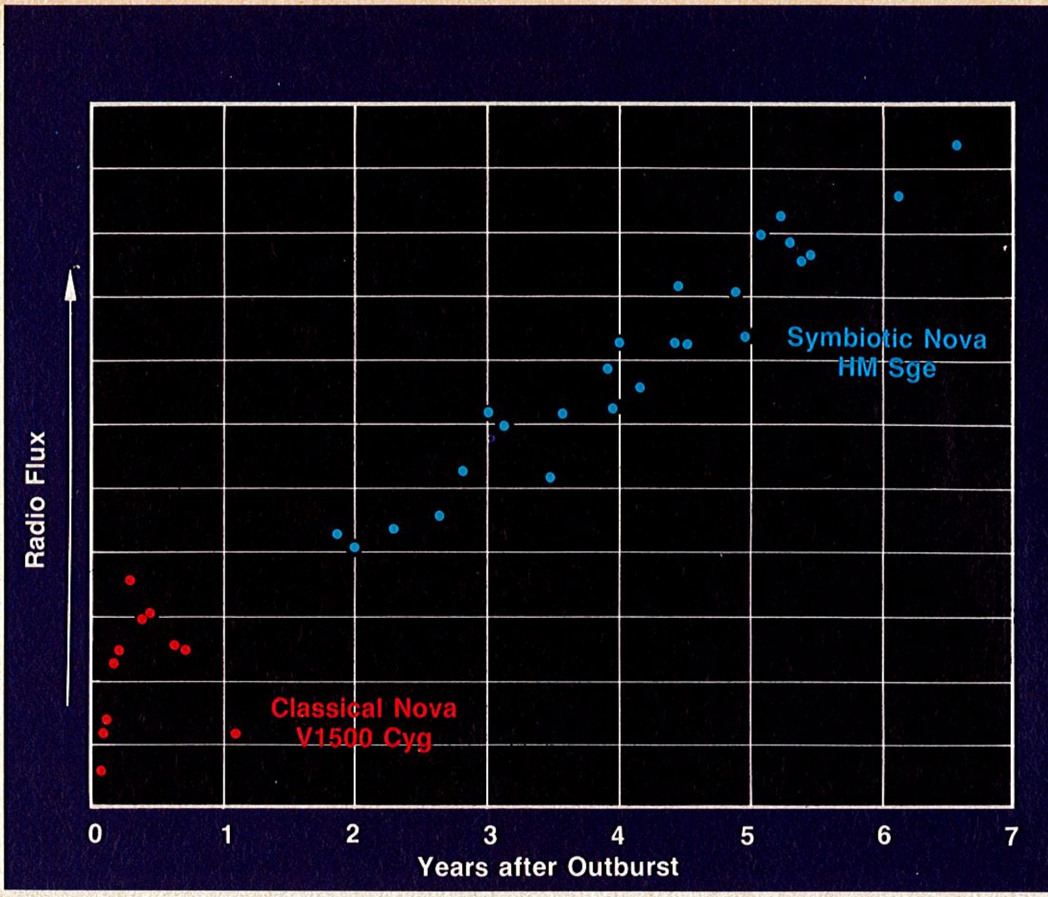
Strong emission lines in a stellar spectrum usually signify the presence of a gaseous nebula surrounding a star with a surface temperature of tens of thousands of degrees. By examining the relative strengths of different atomic lines, astrophysicists can determine the physical properties of the star and its surrounding nebula. This analysis showed that while HM Sagittae has a temperature typical of the central stars of many planetary nebulae, the density of its nebulosity is considerably higher. Since the density of a planetary nebula decreases as it ages and expands, astronomers suggested that HM Sge was a very young planetary nebula.

But in June 1977, Michael Merrill of the Mt. Lemmon Observatory made the first infrared observation of HM Sge. He found the star extremely bright in the infrared, the result of thermal emission from surrounding dust particles. His results indicated that the dust is made of magnesium silicates, which are commonly seen in very *cool* stars. Further observations by other astronomers detected carbon monoxide and water vapor in the stellar atmosphere. For these molecules to survive in a stellar environment, the star's surface temperature must be very low — no greater than 3000° Kelvin. (In comparison, the surface of the Sun is almost twice as hot.) Such a cool surface is usually associated only with red giants — stars well advanced in the late stages of stellar evolution, stars that have yet to create a planetary nebula.

The contradiction of temperatures for HM Sge seemed impossible to reconcile. But it brought to mind a class of strange stars discovered by Paul Merrill in the 1940s, which he called "symbiotic stars." Merrill coined this term for stars that display simultaneously the spectral characteristics of both hot and cool stars. At that time, about two dozen stars fit Merrill's description. Although most of them have no documented novalike outbursts such as that seen in HM Sge, a symbiotic star called V1016 Cygni did undergo a similar episode in 1964. Such outbursts may not, therefore, be isolated instances; they may represent a new, unexplained property of symbiotic stars.

In the late 1970s, when HM Sge began getting all of this attention, I had just published a theory on the nature of V1016 Cyg. I was therefore quite intrigued by this new discovery. Pim Fitzgerald, who discovered the 1964 outburst of V1016 Cyg, and Chris Purton, who measured radio emissions from that star, shared my enthusiasm; we decided to get together and tackle the connection between V1016 Cyg and HM Sge. The detection of radio emission from HM Sge by Paul Feldman of the National Research Council of Canada further convinced us of the similarity between the two stars.

We assumed that the sudden brightening of HM Sge was probably caused by the "creation" of a hot star — possibly the newly exposed hot core of a cool star. We also felt that the silicate dust particles seemed to be part of a strong stellar wind ejected



The radio emission of V1500 Cyg, a classical nova, rose and fell in less than one year. HM Sge, however, has continuously increased in radio brightness since its initial outburst in 1975. The decline in this symbiotic nova's radio output is expected to begin sometime this year.

from a cool star. Such winds are prominent in very old stars and constitute the most common means by which these stars lose mass before their eventual death. The radio emission could arise from a circumstellar envelope created by this wind — a shell of gas ionized by the hot star now present in HM Sge. We embarked on a long-term program to monitor the radio properties of this bizarre star to test our hypothesis.

Our observations at the Algonquin Radio Observatory in Ontario and the Very Large Array radio telescope in New Mexico confirmed the presence of a stellar wind in HM Sge. Furthermore, to our surprise, we found that the radio brightness of the star had slowly but steadily increased. Its brightness at a wavelength of six centimeters, for example, rose by almost a factor of three between 1977 and 1982.

Radio brightening in stars is rare but not unheard of. Classical novae have been known to go through a rise and fall in their radio power over the year following their outburst in visible light. The astonishing thing about this star was the long period of its increase. Extrapolation of our data shows that — as in classical novae — the radio emission will fall again, but probably not before 1984, nine years after its initial outburst. This discovery strengthened the ties between HM Sge and novae. We began to think that its resemblance to planetary nebulae was only superficial.

A planetary nebula is the outer part of a stellar atmosphere ejected into interstellar space near the end of a star's life, when it is a red giant. As this material expands into space, it exposes the core of the red giant, which becomes the central star of a newly formed planetary nebula. Intense ultraviolet light emitted by the extremely hot, exposed core ionizes the detached stellar atmosphere. Light emitted by these ionized atoms makes the planetary nebula visible.

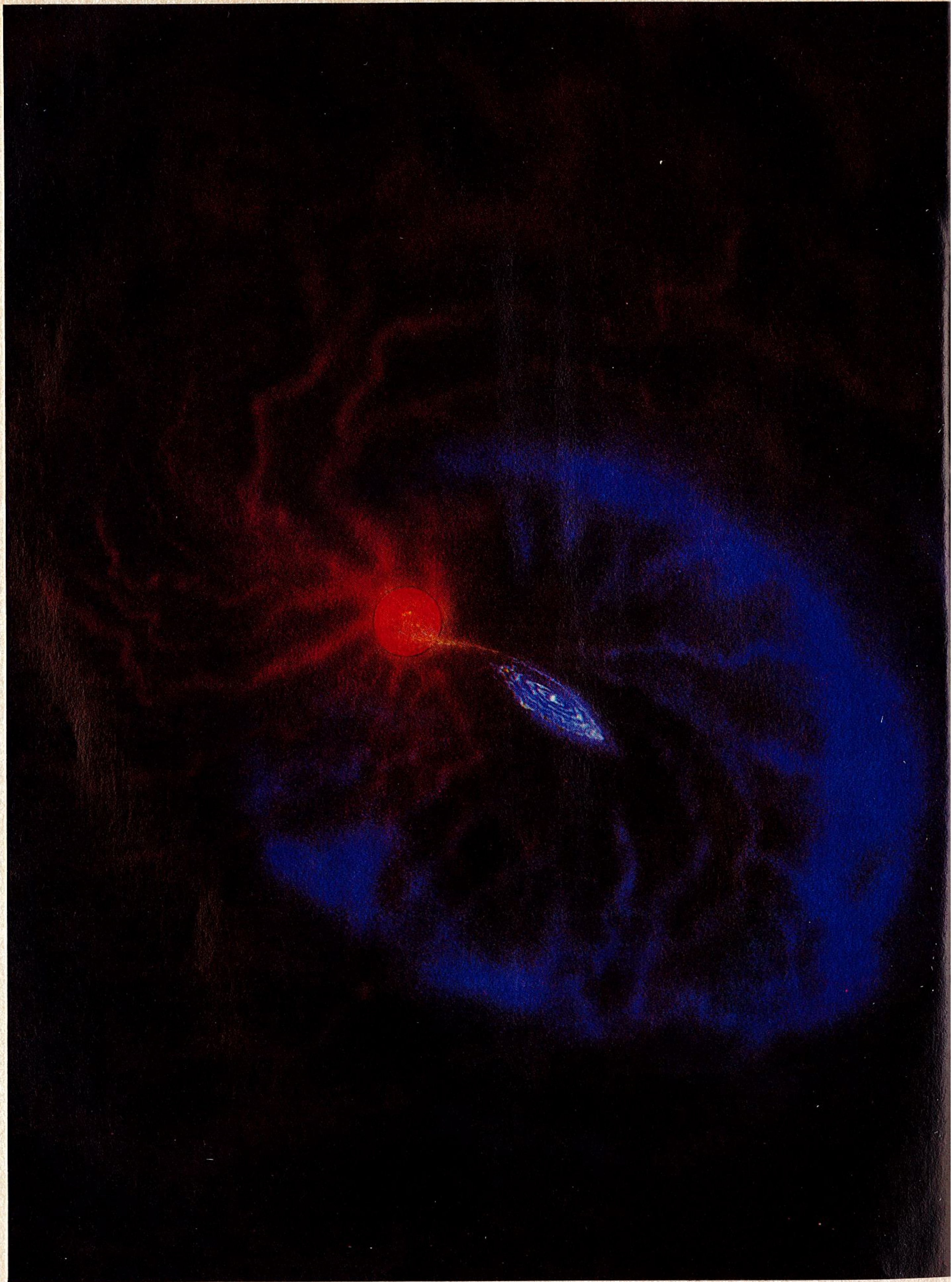
Traditionally astronomers believed that only Sunlike stars form planetary nebulae, but recent observations strongly suggest that stars with masses from one to eight times that of the Sun — over 95 percent of all stars — slough off their outer layers to create these objects. Most stars lose mass by means of intense stellar winds during their red giant phase; by the time they form a planetary nebula their masses are usually about 0.6 solar mass.

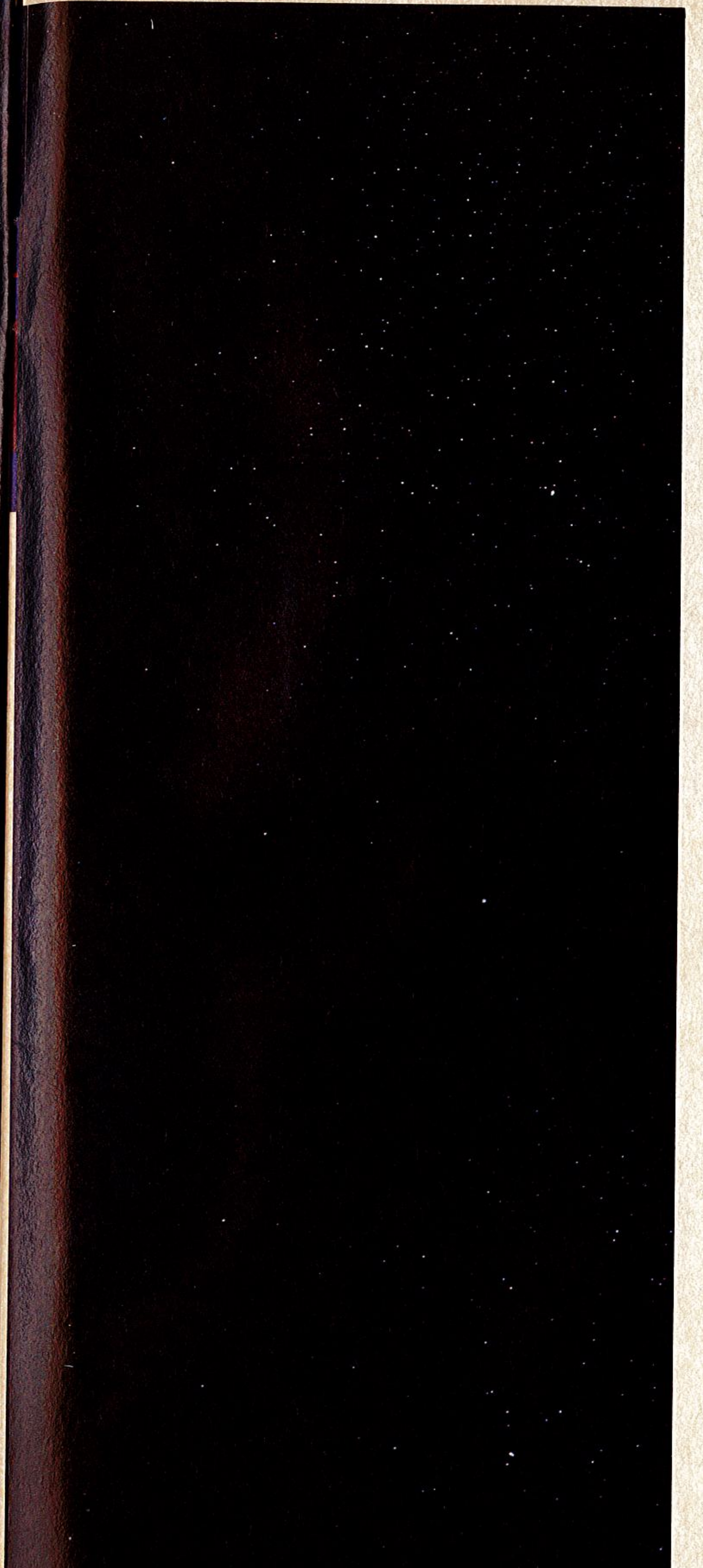
The central stars of planetary nebulae are mostly made up of carbon and oxygen, but maintain their luminosity by burning hydrogen on a thin surface layer. Even so, these stars can shine no longer than 10,000 years. They become hotter as the hydrogen is used up and the stars contract. These stars can have surface temperatures as high as 150,000° K, and shine exclusively in the ultraviolet. When the star finally exhausts its hydrogen reserves, its luminosity drops and it becomes a white dwarf.

The hot stars in symbiotic nova systems like HM Sge are similar to the central stars of planetary nebulae. They are small (a fraction the size of the Sun), hot (surface temperatures close to 100,000° K), and bright (several thousand times the luminosity of the Sun). Their hydrogen content makes up less than one percent of their stellar mass.

The launch of the International Ultraviolet Explorer (IUE) and the Einstein Observatory satellites in 1978 provided opportunities to study the ultraviolet and X-ray emissions from astronomical objects, something that is impossible to do on Earth because of the opacity of our atmosphere. During IUE's testing period, HM Sge was one of the first stars found to show a rich emission-line spectrum in the ultraviolet. And although this star was not on the high-priority observing list of the Einstein satellite, the instrument did detect X-ray emission from it. HM Sagittae was active in nearly all parts of the electromagnetic spectrum, from radio to X-ray wavelengths. In this respect, it is almost unique among stars.

Such a wide range of activity presents particular problems to the theorists who must account for them. To complicate matters further, most of the X-ray, ultraviolet, visible, infrared, and radio light we observe arises from the shell of gas and dust that surrounds the star; the star itself is nowhere to be seen. We can only infer the properties of the star, not measure them — a difficulty that makes astronomical detective work even more challenging. But after much discussion and debate, a consistent picture has gradually emerged from HM Sge's confusing clues.





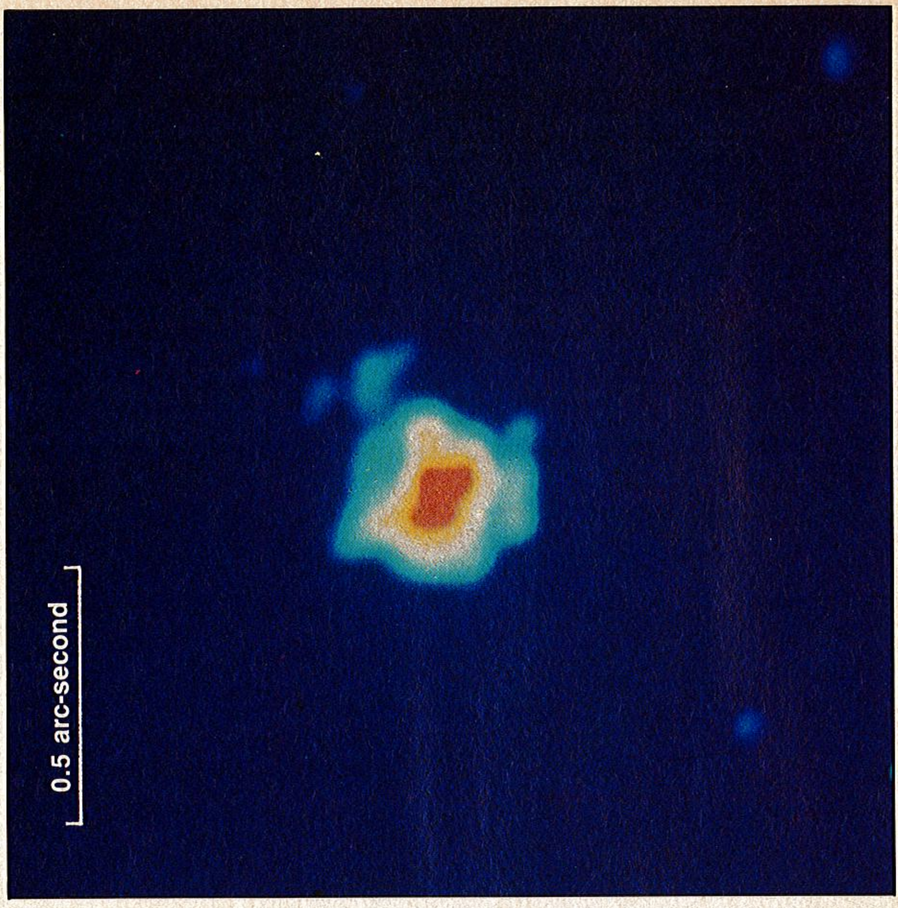
Symbiotic novae like HM Sge seem to be binary systems consisting of a white dwarf and a red giant. The white dwarf accretes matter lost from the red giant, and eventually this hydrogen-rich material begins to undergo fusion and explodes. The explosion ejects gas at speeds exceeding 2000 kilometers per second. This high-speed stellar wind from the white dwarf's hot surface soon collides with the slow, massive wind of its red giant companion. The interaction between these stellar winds creates a dense shell reminiscent of a planetary nebula. Painting by Michael Carroll.

The symbiotic nature of HM Sge is probably due to the presence of *two* stars, the members of a binary system. One is a white dwarf, a star that long ago finished its evolution and died (see the two articles on white dwarfs in the July 1984 issue); the other is a red giant entering the final phase of its life. As a red giant evolves, it grows bigger, brighter, and redder. At some point, its atmosphere becomes unstable and the star begins pulsating. Almost at the same time, the red giant develops a strong stellar wind, throwing off an immense amount of surface material into interstellar space. Although similar to the solar wind, the flow of charged particles emitted by the Sun, red giant winds are about one billion times stronger. According to some estimates, HM Sge may lose 500 trillion tons of matter every second — about one billion times that lost by our Sun.

The strong surface gravity of the white dwarf makes it easy for the star to capture some of the material streaming from its companion. Matter (mostly hydrogen) begins accumulating on the white dwarf's surface. Thousands of years later, enough captured material will have piled onto the white dwarf to produce the critical temperature and pressure for a thermonuclear explosion. Once ignited, the nuclear fires continue until all of the fuel is consumed. During this stage the white dwarf shines like a superhot star. Thanks to the outflow of its giant companion, the white dwarf has been given a brief new life.

This is what we now believe happened to HM Sge in 1975 and to V1016 Cyg in 1964. After nuclear burning commenced on the white dwarf, ultraviolet light emitted by the white dwarf began to ionize the stellar wind around it, creating the numerous atomic emission lines reminiscent of those found in planetary nebulae. Basically, atoms in this gaseous shell convert the ultraviolet light of the white dwarf into visible light, giving the system the appearance of a six-magnitude increase in visual brightness.

The emission of ultraviolet light from the white dwarf is accompanied by a stream of particles expelled from the stellar surface by radiation pressure. The speed of these particles can reach thousands of kilometers per second. They slam into the



A radio "photograph" of HM Sge made with the VLA. The overall size of the object is less than half a second of arc. The extraordinarily high resolution (0.06 arc-second) of the telescope enables astronomers to distinguish the shell (orange) from the red-giant wind (white).

wind from the neighboring red giant and sweep up the material like subatomic snowplows. The amount of matter in the swept-up pile of high-density gas increases rapidly and produces the rising radio emission we observe. By carefully analyzing the emission lines from different atoms, Lee Ann Willson of the State University of Iowa and George Wallerstein of the University of Washington confirmed the existence of the snowplow picture.

Further support of this scenario came in 1982, when Carl Bignell and I took a radio "photograph" of HM Sge at the Very Large Array. Observing at the high frequency of 22 GHz and employing the VLA at its largest configuration, we achieved a resolving power of 0.06 arc-second, or about 20 times better than can be obtained on a large optical telescope. Even though the star's nebula is only a few tenths of an arc-second in size, we were able to discern the red giant wind *and* the high-density shell created by the snowplow process. There is now no doubt that the two stars of this system interact via stellar winds.

Classical novae are also binary systems containing a white dwarf, but there are major differences between symbiotic novae like HM Sge and classical novae. The companion star in a classical nova is a red dwarf, a main-sequence star somewhat less massive than our Sun. When the white dwarf is ignited in a nova outburst, it completely overwhelms the red dwarf's feeble glow. In a symbiotic nova, however, the white dwarf is accompanied by a red *giant*, a star of comparable intrinsic brightness to the white dwarf — even at the peak of the dwarf's outburst. This is what creates the puzzling hot-cool spectrum.

Another difference between these systems is that the red dwarf of a classical nova system does not possess a powerful stellar wind. Although the speed of the red giant wind is lower than that of its white dwarf companion, its mass ejection rate far exceeds that of the much denser white dwarf. It's as though the two stars are engaging in a contest with their respective stellar winds, generating X-ray emission and creating the gaseous shell in the process.

It is a remarkable coincidence that the two stellar components of a symbiotic nova — white dwarf and red giant — are, respectively, the descendant and progenitor of planetary nebulae. When the white dwarf is re-ignited, it "evolves backward," once again becoming the central star of a gaseous nebula. Once the nuclear reactions on its surface stabilize, the white dwarf will evolve normally — just like the central star of a planetary nebula — until it exhausts its nuclear fuel. The white dwarf just retraces its own steps.

Of course, the circumstellar nebula that looks so much like a planetary nebula is formed by the red giant member of the symbiotic system. In a real planetary nebula, the material was ejected when the star was a red giant, then illuminated when that star evolved into a white dwarf. Symbiotic novae just split these roles between two stars. This explains the resemblance between symbiotic novae and planetary nebulae. From an evolutionary point of view, however, they are really more closely related to the systems that produce classical novae.

Stars live finite lives — perhaps 10 to 15 billion years for a low-mass star like our Sun, or a brief flash of glorious existence lasting less than a million years for a really massive star. A lucky few, born with twin brothers in the right range of masses, may rise again and relive part of their later lives by capturing fuel from their companions. This act of resurrection may even occur more than once if the giant companion lives long enough.

The model I've described probably doesn't represent the last word on this exciting phenomenon. But as someone who has puzzled over it for the last seven years, I cannot help but feel that the recognition and modeling of this system was possible only because astronomers have access to the whole electromagnetic spectrum, not just a narrow view confined to visible light. Understanding the symbiotic nova was truly a cooperative effort by astronomers of different specialties working together and sharing information. With the prospect of more and more telescopes stationed in space, this may represent a preview of the way we do astronomy in the future.

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