

White dwarf is caught hurling its outer layers at its red giant companion

Observations of the 12 February outburst and its aftermath are helping astronomers understand novae and supernovae.

About once a century, in our galaxy as in others, a white dwarf accretes enough matter to trigger the fusion of carbon somewhere in its core. A deflagration wave spreads through the stellar interior and releases so much nuclear energy in its wake that the entire star vaporizes. The ferocious explosion is a type Ia supernova.

The threshold mass for igniting a type Ia supernova is thought to be just below the Chandrasekhar limit of 1.4 solar masses. Given that newborn white dwarfs weigh no more than $0.8 M_{\odot}$, it's long been clear that white dwarfs need help reaching the supernova threshold. What's harder to understand is how they get there.

Supplying matter isn't a problem. Like other stars, about half of all white dwarfs have binary companions. Our galaxy abounds in binaries whose spectra and light curves evince the presence of a white dwarf feeding on its companion's outer layers.

But material that piles onto the hot white dwarf surface is susceptible to thermonuclear blowup, just like the star itself. When the accumulated material explodes, the fusion products can easily acquire enough kinetic energy to escape the white dwarf's gravitational grip.

Those surface eruptions, whose manifestations astronomers call novae, come in various types and occur in our galaxy thousands of times more often than supernovae. Despite the abundance, it's unclear just what type of accreting white dwarf somehow succeeds in accumulating enough mass to beget the rather rare type Ia supernova.

Now, thanks to a nearby nova called RS Ophiuchi, astronomers are getting their most detailed look at the physics of nova outbursts. The observations, which span the electromagnetic spectrum from radio to x ray, have revealed for the first time how much accreted matter is shed in a nova outburst.¹

And by analyzing the emission from the cooling, post-outburst white dwarf, astronomers hope to determine how

much accreted matter remains. That RS Ophiuchi's white dwarf has gained weight is already clear: Its mass is close to a ready-to-pop $1.4 M_{\odot}$.

Recurrent and symbiotic

Stargazers have noticed novae since antiquity. But only 10 novae, RS Ophiuchi among them, have ever been caught in outburst more than once. RS Ophiuchi flared up in 1985, 1967, 1958, 1933, and 1898 and possibly in 1944 and 1902. Hiroaki Narumi and Kiyotaka Kanai of Japan spotted the new outburst on 12 February and promptly alerted their fellow astronomers.

From the previous outbursts, astronomers identified RS Ophiuchi as a symbiotic binary: a white dwarf and red giant orbiting their mutual center of mass. Figure 1 shows what it might look like. The pairing is unusual. So far, only about 200 symbiotics have been cataloged in our galaxy.

What Narumi and Kanai witnessed was the thermonuclear explosion on the white dwarf surface. As the burning

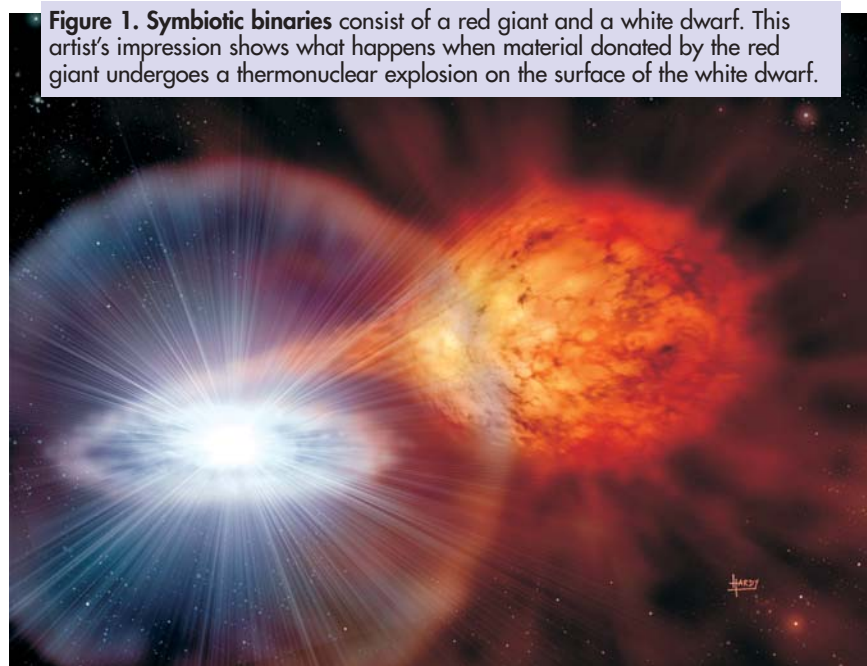
layer lifts off, it expands adiabatically and cools. By March, the ejecta's optical flux had plunged to one thousandth of its 4.5-magnitude peak.

How an outburst plays out depends largely on the mass of the ejecta and the density and distribution of the enveloping material. Given the short time between outbursts, the ejecta shed by RS Ophiuchi's white dwarf are low in mass; but the wind blowing off the red giant is thick. One expects the ejecta to decelerate rapidly—more like a wiffle-ball shot through water than a baseball shot through air.

As they slam into the red giant's wind, the foremost ejecta launch a forward shock, sweep up material, and slow down. Then, like a stalled car at a green light, they're rear-ended by ejecta following behind. The result is a reverse shock, which travels back toward the white dwarf.

Both shocks compress and heat material in their path to x-ray-emitting temperatures, 10^6 – 10^8 K. For RS Ophiuchi's combination of low-mass ejecta

Figure 1. Symbiotic binaries consist of a red giant and a white dwarf. This artist's impression shows what happens when material donated by the red giant undergoes a thermonuclear explosion on the surface of the white dwarf.



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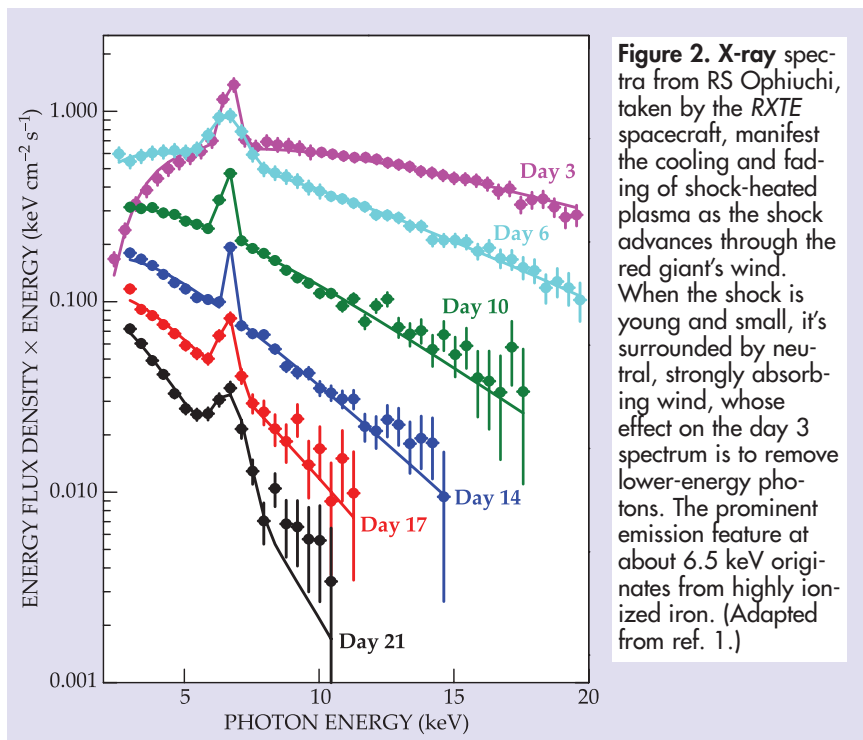


Figure 2. X-ray spectra from RS Ophiuchi, taken by the *RXTE* spacecraft, manifest the cooling and fading of shock-heated plasma as the shock advances through the red giant's wind. When the shock is young and small, it's surrounded by neutral, strongly absorbing wind, whose effect on the day 3 spectrum is to remove lower-energy photons. The prominent emission feature at about 6.5 keV originates from highly ionized iron. (Adapted from ref. 1.)

and thick wind, the forward shock predominates.

Slowing and cooling

Just days after Narumi and Kanai's alert, NASA's *RXTE*¹ and *Swift*² spacecraft pointed at RS Ophiuchi and detected shock-heated, x-ray emitting plasma.

Of the two observatories, *RXTE* is the more sensitive to the hottest, freshest plasma. Figure 2 shows a time sequence of *RXTE* spectra analyzed by Jeno Sokoloski, of the Harvard-Smithsonian Center for Astrophysics, and her collaborators.¹ A reasonable fit is provided by single-temperature thermal bremsstrahlung with the addition of line emission from highly ionized iron. Both spectral components are consistent with optically thin plasma.

How hot the plasma gets depends on how fast the shock moves through it. Theorists predict the plasma's temperature is proportional to the square of the shock's speed u . From day 3 to day 21, before the plasma cooled and faded out of *RXTE*'s reach, u fell with elapsed time t at a rate proportional to $t^{-1/3}$. The rate is consistent with the theory that Leonid Sedov, G. I. Taylor, and John von Neumann developed independently during World War II to describe bomb blasts.

Extrapolating backward in time, Sokoloski and her collaborators determined that the shock began decelerating 1.7 days after the outburst. At that point, according to the bomb blast the-

ory, the hot, swept-up gas was a few times more massive than the ejecta. Estimating the wind density near the white dwarf (10^9 atoms cm^{-3}), Sokoloski and her collaborators deduced an ejecta mass of order $10^{-7} M_{\odot}$, which is about the mass of Mercury.

Figure 2 shows not only a decrease in temperature but also a decrease in luminosity. At its initial peak, the shock-heated plasma glowed with a total luminosity 300 times higher than the Sun's. By day 21, it had waned by an order of magnitude at a rate proportional to $t^{-5/3}$. A spherically expanding shock of the sort expected from bombs and novae should fade at a rate proportional to t^{-1} . RS Ophiuchi's faster fade could have arisen from a shock that expanded more slowly in some directions than in others.

NASA's *Chandra* spacecraft began observing RS Ophiuchi two weeks after the 12 February outburst. According to Jeremy Drake of the Harvard-Smithsonian Center for Astrophysics, the emission lines detected by the spacecraft's diffraction grating have profiles inconsistent with a spherical distribution.

More direct evidence of nonuniform expansion comes from radio observations. Soon after the outburst, a host of radio telescopes began monitoring the shock's progress. Unlike the case for supernovae, the shock wave slowed so rapidly that it barely expanded beyond the outer reaches of the red giant's wind. Fortunately, RS Ophiuchi is just

close enough that networks of widely spaced radio telescopes could resolve the expanding shell.

The image in figure 3, reconstructed from data taken on 26 February, represents the earliest spatially resolved view of the shock from a nova or supernova. The emission comes from relativistic electrons gyrating around magnetic fields and is strongest where the electrons are densest and the photon absorption weakest. In the red giant's wind, one expects the density to fall off with distance r from the star as $1/r^2$ except in the orbital plane, where gravitational focusing enhances the density.

Tim O'Brien of the University of Manchester and his collaborators have modeled the sequence of radio images in terms of a peanut-shaped shell.³ At the earliest stages, the radio emission was brightest at the peanut's high-density waist, only one side of which is visible at first because of obscuration. Later, the peanut's two ends emerged as expanding blobs, one after the other.

Surface leftovers

As the shock expands, it ionizes and removes the x-ray-absorbing gas that shrouds the white dwarf. *Swift*, which continues to monitor RS Ophiuchi, tracked the gradual clearing away of obscuring material, which again matched theoretical expectations.² Then, on day 30, *Swift* and, later, *Chandra* detected material burning on the white dwarf surface.

Long after an outburst, one expects the white dwarf to be quiescent, its spectrum more or less that of a slowly cooling blackbody. But at day 40, the

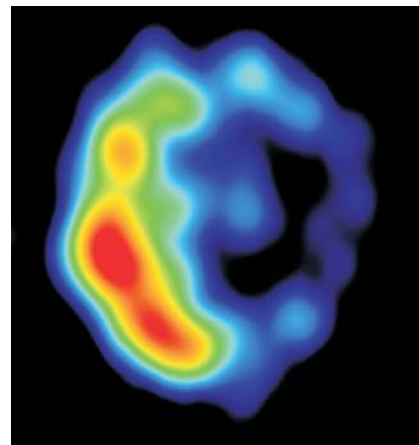


Figure 3. The first radio image of the expanding shock in RS Ophiuchi was taken by the Very Long Baseline Array two weeks after the outburst. At that stage, the shocked region was no bigger than Saturn's orbit. (Adapted from ref. 3.)

emission rose and fell erratically. Intriguingly, the variability included a roughly periodic signal at 35 seconds.

Though short, the period could arise from the white dwarf's spin. In the AE Aquarii system, for example, the accreting white dwarf spins with a slightly shorter period of 33 seconds. Alternatively, some sort of surface wave or convection phenomenon could be at work.

Regardless of the origin of the period, it should be possible to infer how much accreted mass remained on the white dwarf after the outburst. The *Swift* team hopes to do so soon.

The low ejecta mass already implies that the white dwarf in RS Ophiuchi

has held onto some of its accreted material after each outburst. Only a massive, near-Chandrasekhar-mass star could compress $10^{-7} M_{\odot}$ so much that it explodes.

Still, it's not obvious that RS Ophiuchi, when it eventually pops, will resemble type Ia supernovae. The quest to identify their progenitors continues.

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References

1. J. L. Sokoloski, G. J. M. Luna, K. Mukai, S. J. Kenyon, *Nature* **442**, 276 (2006).
2. M. F. Bode et al., *Astrophys. J.* (in press). Also available at <http://arxiv.org/abs/astro-ph/0604618>.
3. T. J. O'Brien et al., *Nature* **442**, 279 (2006).

Good music unfolds in small steps

Geometry and topology allow music theorists to quantitatively analyze a technique that composers have intuitively practiced for centuries.

Even the most tin-eared of listeners would hardly confuse a Johann Sebastian Bach piano prelude with a Keith Jarrett jazz improvisation. But despite the 300 years of stylistic evolutions that separate the two masters, they and other great composers share an important musical trait: They move from chord to chord in what feels like a smooth-sounding, economical way.

That economy has manifestations on the printed musical page where, as figure 1 shows, notes of one chord are only slightly displaced to create the following chord. Likewise, Jarrett's fingers need not move much as he shifts from one chord to the next.

The printed page, however, obscures an important musical quality that is apparent when good music is heard. Music generally is perceived not merely as a series of chords sounded in succession, but also as a series of melodic

lines, "voices," unfolding in time and combining to form harmonies. So, for example, one listening to the passage in figure 1a would hear the simultaneous melodies of upper, middle, and lower voices. Part of what we admire in good music is the voice leadings—that is, how voices move from chord to chord.

Music pedagogues have been teaching how to write attractive voice leadings since before Bach. But some who study music have not been satisfied with traditional intuitive descriptions; their goal has been to quantify the notion of economical music writing. A striking example is the *tonnetz* (tone network), popularized in the late 19th century by Hugo Riemann. In the network, the major and minor triads common in canonical Western music are represented as triangles tiling a plane. The most efficient voice leadings connect triangles that are next to each other.

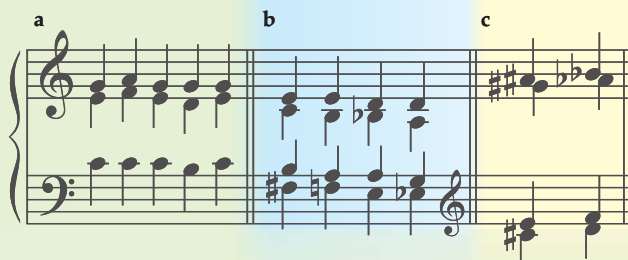


Figure 1. Economical composition uses minimal note changes to move from chord to chord. Examples shown include (a) a cadence in the 18th-century style, (b) a common jazz piano pattern, and (c) the first two chords of Claude Debussy's *Prelude to the Afternoon of a Faun*, which premiered in 1894. (Adapted from ref. 1, which includes a sound file online.)