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# The new science of NOVAE

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**The discovery of γ-ray emission from novae has been used not only to better understand sudden brightening events but also to answer some old questions and raise new ones.**

On 8 November 2016, Kwan-Lok Li of Michigan State University discovered a new bright source of $\gamma$ rays in the constellation Sagittarius using the Large Area Telescope (LAT) aboard the *Fermi Gamma-Ray Space Telescope*. Li and his colleagues had been inspecting the LAT data from that part of the sky for any $\gamma$ rays from a nova, in which the light from a previously obscure star suddenly becomes much brighter. No $\gamma$-ray source had been seen at the location until two weeks after the start of the optical eruption (see figure 1). Although such events were first discovered in 2010, the 2016 eruption is the most dramatic example of the sudden appearance of $\gamma$ rays in optical novae.

A nova eruption occurs in binary star systems containing a white dwarf star, the dense nuclear ash of a low-mass star supported by the quantum mechanical repulsive force among electrons (see box 1). Eruptions, like the one shown in the opening photo, are usually found because of their spectacular and sudden optical brightening, which occurs over a matter of days. Some nearby ones—about a quarter of the way to the Milky Way's center or closer—are bright enough to see with the naked eye. The novae in nearby galaxies are also bright enough to be observable. But of the estimated 50 or so nova eruptions per year in the Milky Way,[1] only about 10 are actually discovered because of interference from the Sun, crowding of stars in the galactic center region, and dust obscuration.

After peak intensity, the nova typically takes weeks or months to dim by a factor of 10. Spectroscopic observations show that matter is ejected from novae at velocities ranging from about 300 km/s to almost 10 000 km/s. Novae with high-velocity ejecta fade more quickly, a property that was best studied in a sample of novae observed in the Andromeda galaxy.[2]

The companion star supplies the white dwarf with fresh, hydrogen-rich fuel for the nova eruption. With enough fuel, the material on the surface of the white dwarf achieves a critically high temperature and pressure, and a thermonuclear runaway (TNR) ensues, which lasts for about 1000 seconds and generates more than $10^{45}$ ergs of energy. In many cases, the TNR is strong enough to violently eject much of the matter the white dwarf accumulated from its companion (see box 2). And much like in volcanic eruptions, the ejecta provide most of the light show.

Nova eruptions leave the underlying binary systems largely unchanged. The companion star is most often a red dwarf, which is smaller than the Sun. Some 10–30% of all novae come from a white dwarf paired with a red giant. But most such binaries have never been seen to have nova eruptions. Evidence of a nova eruption becomes difficult to find a few decades or centuries after it explodes. All that can be seen is that the white dwarf is accreting fresh new fuel, so eventually a new nova eruption will occur. The white dwarf usually takes from a decade to a few hundred thousand years to accumulate enough material to trigger a TNR, though in one spectacular case in the Andromeda galaxy, the accumulation takes just one year.[3]

Nova ejecta are multiphased. Recent multiwavelength observations make it apparent that hot plasma and cold dust coexist with the warm (10 000 K) phase of ejecta. In particular, the surprise discovery of the strong $\gamma$-ray emission from novae has led to renewed interest in the hot phase of the ejecta. With multiwavelength observations pushing theoretical developments, the mystery of the strong $\gamma$ rays from novae is being unraveled.

## The warm phase

At optical peak, the emission from a nova is dominated by visible light, emitted by warm ejecta, that readily absorbs incoming photons. The visible-light photons interact with material deep inside the ejecta mostly by electron scattering. The process creates a surface of last scattering. As the ejecta expand and thin out, the surface recedes, and instruments can see farther into the ejecta. As the size of the surface shrinks, its effective temperature increases. The luminosity of a nova remains roughly constant because nuclear fusion continues at the white dwarf surface at a quasi-steady rate. As the peak of the spectral energy distribution moves from visible light to the UV, the photospheric emission from the white dwarf can escape without interacting much with the ejecta. At that stage, the photosphere has a temperature between 500 000 K and 1 million K, and much of its emission is in the extreme UV, which is easily absorbed by the interstellar medium. Although the UV emission becomes more difficult to observe, the photosphere does emit detectable, low-energy x rays. The *Neil Gehrels Swift Observatory* can respond rapidly to unforeseen celestial events and has provided a wealth of details regarding the visible, UV, and soft x-ray behavior of novae.[4]

Radio and IR wavelengths provide even more information about novae. By assuming a reasonable density distribution in the ejecta, one can infer its total mass from a single radio spectrum. With multiple radio spectra, both the density distribution and the total mass of the ejecta may be constrained.[5] At IR and radio wavelengths, free electrons scatter off ions without being captured: That free-free process, which dominates emission and absorption, keeps nova ejecta opaque to IR and radio light even after they become transparent to visible light. For typical expected densities and for temperatures of 10 000 K, nova ejecta emit free-free radio emission from opaque ejecta for several months (see figure 2). During that time, the angular diameter of the ejecta increases steadily, so the flux of radio and IR photons increases as the time after ejection squared. Knowing the radial velocity of expansion from spectroscopy and assuming that the nova is spherically symmetrical, researchers can infer the distance to the nova. Eventually the ejecta become transparent even to IR and radio emission.

### Box 1. Changes in white dwarf mass

In binary systems that host nova eruptions, accretion plays multiple roles. Between eruptions, it is an important, sometimes dominant source of luminosity and a source of additional mass for the white dwarf. During eruptions, previously accreted material becomes the source of fuel for the thermonuclear runaways (TNRs). The white dwarf therefore gains mass between successive eruptions and loses mass during nova eruptions as the energy of the event ejects the accreted matter. So over many nova cycles, do the white dwarfs gain or lose mass? The answer obviously determines the long-term future of the binaries, which includes the possibility that some become type Ia supernovae.

Theoretically, a key consideration in answering the question is mixing processes. TNRs in novae are fusion reactions, either a carbon-nitrogen-oxygen cycle or an oxygen-neon-magnesium one, and mixing between the white dwarf's envelope and its core material can alter the strength of the TNR. How and how much core material mixes is a matter of debate. Overabundances of elements such as nitrogen and neon are often seen in nova ejecta. That observation, suggesting that some core material is ejected, favors mass loss. However, white dwarfs accreting material from red dwarf companions are more massive than those in white dwarf–red dwarf binaries that haven't yet begun the accretion process, which suggests mass gain.

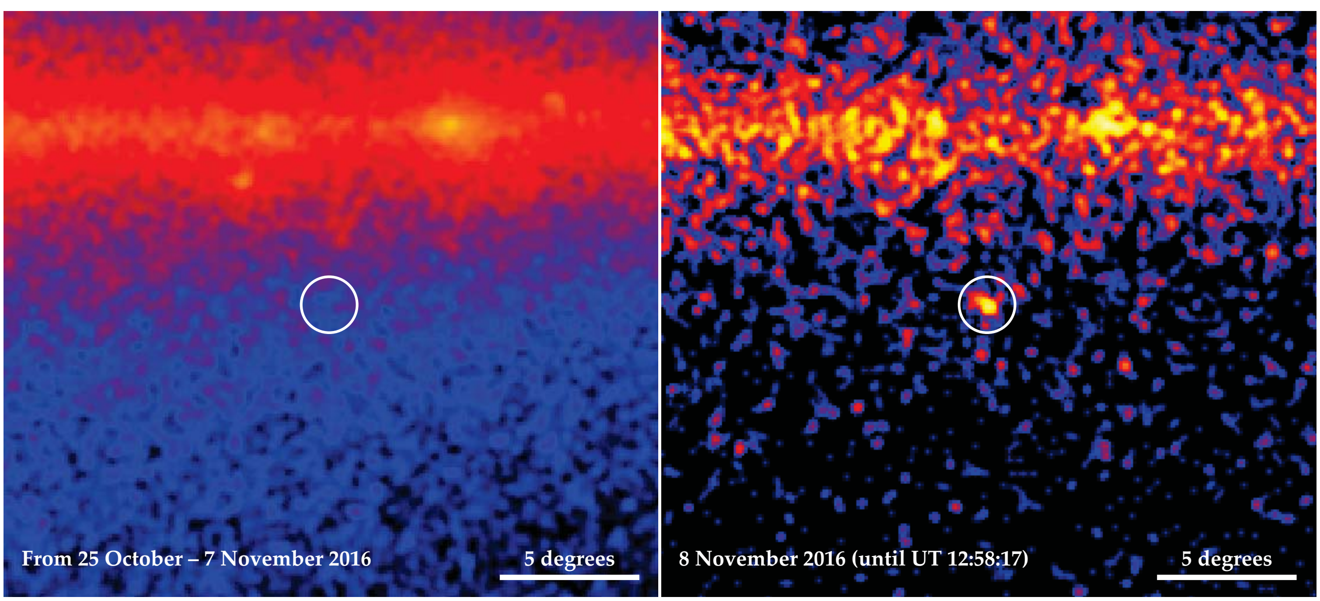


**FIGURE 1. THE REGION OF THE SKY AROUND THE NOVA ASASSN-16ma** before (left) and after (right) the sudden appearance of $\gamma$ rays. The images were taken by the Large Area Telescope aboard the *Fermi Gamma-Ray Space Telescope*. (Courtesy of Kwan-Lok Li, Michigan State University.)

The ENova collaboration, which includes the authors, has used the Karl G. Jansky Very Large Array (VLA) in New Mexico, the world's premier radio telescope, to observe more than 20 novae. They are usually well observed using ground-based optical and IR photometry and spectroscopy plus x-ray and UV monitoring with *Swift* and other satellites. Often a game of hurry-up-and-wait is played: When new novae are discovered, early observations must be arranged quickly, and then astronomers must wait months and sometimes years for a nova to first brighten and then fade back to undetectability. The ENova team has published ejecta-mass estimates on four novae so far, ranging from $10^{-5}$ to $3 \times 10^{-4}$ solar masses. For several novae, VLA radio observations revealed something even more interesting than their ejecta masses. Flares in radio brightness during the first month after the TNR could be a major clue in the nova $\gamma$-ray mystery.

## Warm ejecta are complicated

In the simplest case, ejecta from novae are spherically symmetric and were ejected all at once at the time of the TNR. They have a simple density structure such that $\rho \propto r^{-2}$, where $\rho$ is density and $r$ is the distance from the white dwarf, which results from the spread in velocity at the time of ejection, and they have a uniform and constant temperature. Real novae are far more complicated.

Ejecta from novae must vary in temperature both temporally and spatially. If the ejecta are treated as a noninteracting, dynamically expanding shell, one would expect them to adiabatically cool quickly. Observations show that the ejecta remain largely ionized. Otherwise, free-free emission would abruptly cease when the ejecta recombine, an event that has never been seen. Possible sources of heat that have been known for decades include *in situ* decay of radioactive isotopes synthesized during the TNR and irradiation by the central white dwarf, which remains luminous due to continued quasi-steady nuclear burning.

Ejecta from novae have a complicated, clumpy density structure. A *Hubble Space Telescope* image of the remnant of GK Persei (Nova Persei 1901) shows the clumpiness in exquisite detail. In principle, known instabilities can lead to such density inhomogeneity. However, astronomers do not know when during the nova eruption such clumps form and grow. To determine the ejecta mass from radio data, one can parameterize the unknown degree of clumping using a volume-filling factor. Then the data are consistent with a larger range of ejecta masses.

Ejecta may not be expelled promptly during the TNR. In the T Pyxidis nova, the rising part of the radio light curves do not match the expected $t^2$ dependence if it's assumed that the bulk of the mass was ejected at the onset of its 2010 eruption and TNR. A model with an ejection 50 days after the TNR fits the data well.[6] Similarly, delayed ejection is inferred from the directly imaged expansion history of radio-emitting ejecta in V959 Monocerotis and from x-ray observations of both novae.

Ejecta probably consist of at least two flows that collide with each other. That composition has been learned

## Box 2. Nucleosynthesis products

The thermonuclear runaway (TNR) in novae produces copious amounts of radioactive isotopes such as nitrogen-13, beryllium-7, and aluminum-26. Novae could explain the origin of the Milky Way's 1.809 MeV diffuse emission line from the radioactive decay of the $^{26}$Al isotope.[15] In the immediate aftermath of the TNR, radioactive isotopes with a half-life of minutes to days are expected to make individual novae transient sources. The 511 keV line is produced by annihilation of positrons from $\beta^+$ decay, and the 478 keV line from $^7$Be decay. Although none have been detected to date, the estimated fluxes from nucleosynthesis models and the sensitivity limits of the current generation of instruments point toward a tantalizingly nearby nova.

The total mass ejected by novae—about $10^{-3}$ solar masses per year assuming 50 novae—is significantly smaller than that for core-collapse supernovae, which would be 0.1 solar masses per year assuming values of 1 core-collapse supernova per century and 10 solar masses per supernova. Yet novae probably contribute significantly to the galactic chemical evolution of a few select elements or isotopes. One prominent example is lithium, a fragile element whose origin has long been debated. The recent discovery[16] of absorption lines of $^7$Be in V339 Delphini and $^7$Li in V1369 Centauri soon after the TNR suggests that $^7$Be may be created during eruptions in quantities large enough that novae could be a major source of lithium.

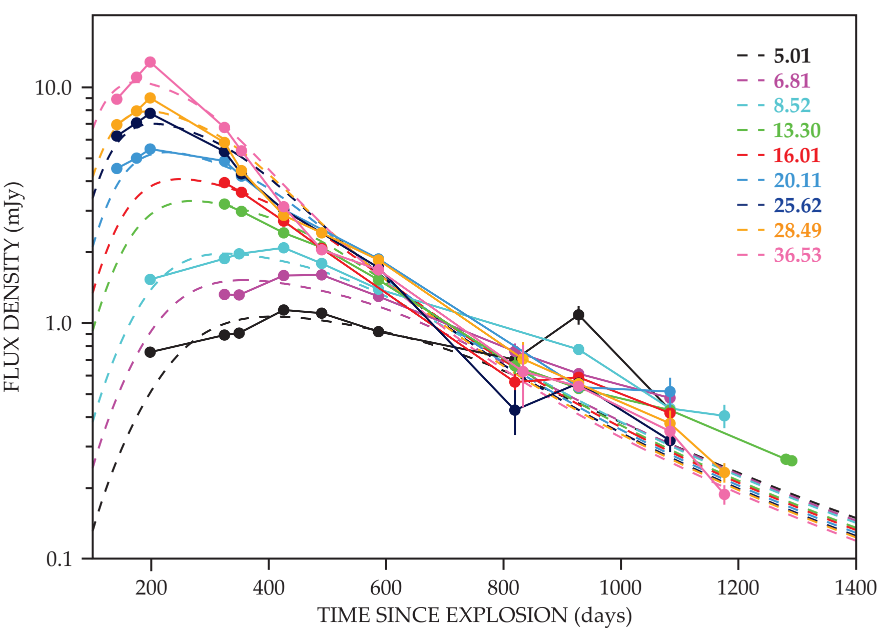


**FIGURE 2. THE LIGHT CURVES OF THE NOVA V1723 AQL** show the brightness at several gigahertz radio frequencies as a function of time starting 100 days after the eruption of ejecta. The modeled thermal emissions from the expanding ejecta (dashed lines) are similar to observations (solid lines). (Adapted from ref. 14.)

from observations of shocks and from the morphology of ejecta.

## A shocking hot phase

In March 2010 a team of researchers using the *Fermi* satellite discovered a transient $\gamma$-ray source in the constellation Cygnus. An earlier x-ray observation by *Swift* of that region in the sky confirmed that the mystery object that produced the $\gamma$-ray source was a nova called V407 Cygni. Learning that novae can produce $\gamma$-ray emission[7] has opened a new field of science for *Fermi* and new avenues of nova research.

To generate $\gamma$ rays, particles must be accelerated to relativistic energies, which requires a strong shock. Because V407 Cygni has a red-giant mass donor, astronomers believed that the presence of the red giant was the key to producing $\gamma$ rays. Strong shocks are expected in such cases because a red giant has a massive, slow stellar wind that engulfs the white dwarf. The nova ejecta, therefore, immediately collide with the red giant's wind and create a strong shock at the interface. In fact, researchers have explained certain features of another embedded nova, RS Ophiuchi, using particle acceleration.[8] Once particles are accelerated, $\gamma$ rays are generated in either the hadronic process, in which accelerated protons collide with matter to create neutral pions that then decay into $\gamma$-ray photons, or the leptonic process, in which visible light or IR photons interact with high-energy electrons and attain high energies. No conclusive evidence supports either scenario yet, although theorists may be leaning toward the hadronic model.

The initial consensus that only novae embedded in the strong wind of the mass donors would emit $\gamma$ rays was proven wrong in 2012 when $\gamma$-ray emissions were discovered from two novae whose red dwarf companion stars lacked strong winds. By now *Fermi* has detected more than a dozen novae. Even novae that are the brightest in $\gamma$ rays are not much above *Fermi* LAT's detection limit, with a dynamic range in detected flux of about 10. The distances to all galactic novae in the *Fermi* era probably have a range of a factor of 10, or a flux range of a factor of 100 for a single value of intrinsic luminosity. Distance is a major factor in determining which novae can be detected with *Fermi*. Many astronomers now think that most, if not all, novae emit $\gamma$ rays, although the existing data suggest that some produce more $\gamma$ rays than others.

Even before the discovery of $\gamma$ rays, shocks were known to be common in novae. One line of evidence is the early radio emission detected from some novae. For example, the radio emission from the 2010 eruption of V1723 Aquilae became so bright it could not have been produced by the warm ejecta. A shock was required, either to create thermal free-free emission from a large amount of $10^6$ K gas or to produce nonthermal emission from accelerated electrons. Another line of evidence is the optically thin, thermal x-ray emission detected from many novae in the 0.5–10 keV band. Shocks with velocities in the 1000–3000 km/s range, which are compatible with the outflow velocities measured using optical spectroscopy, imply plasma temperatures of 10 million K to 100 million K. However, the measured luminosities of the thermal x rays are about $10^{35}$ ergs/s or less. The fact that the observed $\gamma$-ray luminosity is comparable to the observed thermal x-ray luminosity is a huge surprise. Theory predicts that the majority of shock power should remain with thermal particles and that only about 1% of the total shock energy transfers to the accelerated particles. Either the shocks in novae are unexpectedly efficient at accelerating particles, or some more powerful shock is yet to be observed.

It appears that shocks, embedded or not, are ubiquitous in novae and perhaps much more powerful than had been realized. Shocks may even supply some power to the optical emission from a nova. Unlike other astrophysical shocks that accelerate particles, the early shocks in novae arise from modest velocities of about 1000 km/s and the material's high density. Therefore, the thermal x-ray emission behind the shocks can appear as optical emissions because they can be quickly absorbed and reprocessed by the surrounding unshocked ejecta.[9] That model provides a plausible explanation for the behavior of the ASASSN-16ma nova.[10] At optical peak, the $\gamma$ rays suddenly turned on, as shown in figure 1, and remained strong for nine days. During that period, the $\gamma$-ray flux was strongly correlated with the optical flux (figure 1 of reference 10). Such a correlation would be a natural consequence if the $\gamma$ rays and the optical emission were energized by the same shock whose power fluctuated.

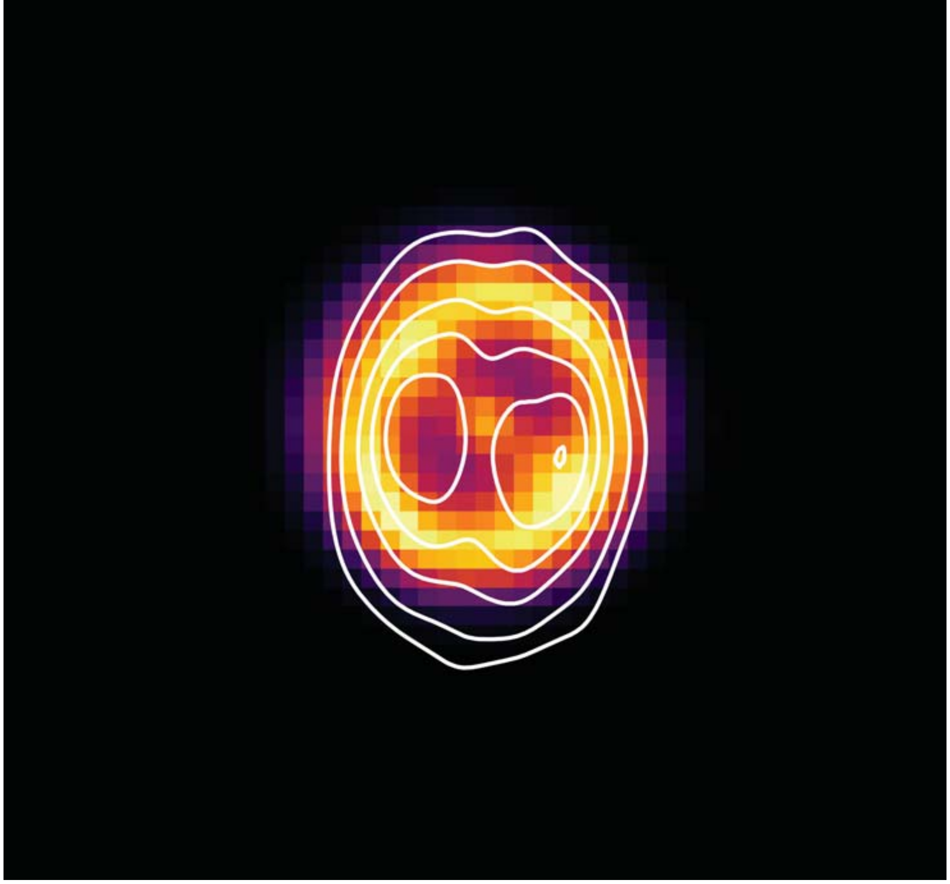

**FIGURE 3. THE NOVA V5668 SAGITTARII** can be seen by combining optical imagery (color) from the *Hubble Space Telescope* and radio images (white contours) from the Very Large Array telescope. The optical image shows a ring-like structure, and the radio image is dominated by two bright, central knots. Together, the images suggest that the visible nova shape could be a torus viewed from an edge-on perspective. (Courtesy of Justin Linford, National Radio Astronomy Observatory.)

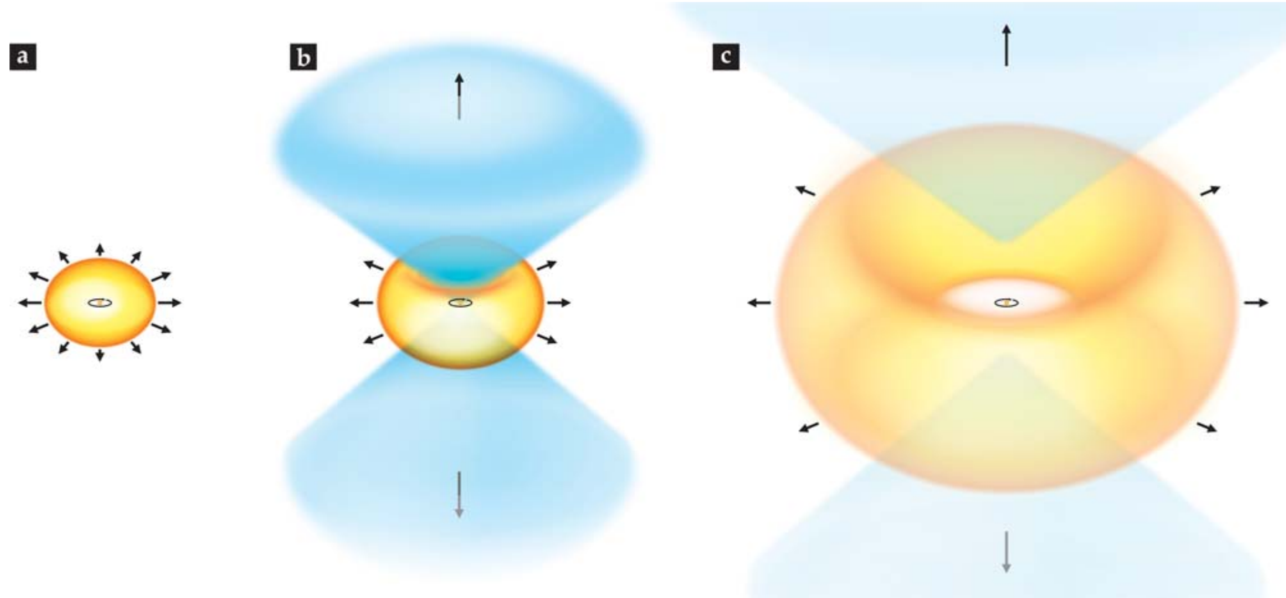


**FIGURE 4. A NOVA CHANGES SHAPE OVER TIME.** Soon after thermonuclear runaway, an envelope of dense material (yellow) begins to surround the binary system **(a)**, which has the shape of an equatorial torus. **(b)** As the nova explosion continues, the white dwarf energizes fast-moving wind (blue) that flows out toward the low-density conical poles of the torus. Once the wind ceases **(c)**, the outflow detaches from the binary and decreases in density as it expands. The slower-moving material in the equatorial torus remains dense and will be the primary feature observed by radio telescopes. (Courtesy of Theophilus Britt Griswold, NASA.)

The ability of the ejecta to absorb x rays depends on the energy of the x-ray photon. Lower-energy x rays are more easily absorbed. The *NuSTAR* satellite is the first focusing x-ray telescope in orbit searching for x rays above 10 keV and has the best chance of detecting x rays from novae soon after an eruption, when the emission region is located deep inside the ejecta. One study successfully detected the nova V5855 Sagittarii from x rays using *NuSTAR* concurrent with the $\gamma$-ray detection by *Fermi*.[11] However, a puzzle still remains: The x-ray luminosity of the deeply embedded shock is still inadequate to explain the $\gamma$-ray luminosity unless the shock is unexpectedly efficient at particle acceleration.

## Ejecta morphology

Direct imaging of the ejecta from novae is a challenging task. They are bright shortly after the TNR and fade over time. During the early period when novae are bright, their angular scales are modest. For a nearby nova, like many of the ones detected with *Fermi*, the ejecta will have a radius of just 0.1 arcsec one year after the start of the eruption. Ground-based optical imaging of novae sometimes shows spatially resolved nova shells on arcsecond scales as much as a century after the TNR, but only after the shells have expanded for several years or more. Direct imaging within a few years of a nova eruption requires the highest spatial resolutions available, often using *Hubble*, and radio observations with the VLA (see figure 3) and very long baseline interferometry.

Many nova shells are clearly elongated rather than circular. Radial velocity studies of optical-emission-line profiles also show evidence of structures, such as bipolarity and an equatorial ring. One likely origin of the nonspherical shape is that the ejecta are influenced by the binary companion.[12] The difficulty of that interpretation is that fast outflows typical of nova eruptions are less susceptible to the influence of the companion star because they spend little time in the immediate vicinity of the binary, where the effect is large.

When detailed imaging is feasible, such shapes as an equatorial torus and polar cone are often seen, sometimes with additional structures. Simulations that include the effect of binary motion can re-create such morphology at least in broad outline. Radio observations of the V959 Monocerotis, one of the novae that were detected with *Fermi*, helped uncover its structure.[13] Radio data from the VLA trace the warm ejecta, which appeared elongated in the east–west direction four months after the eruption when the fast, biconical wind dominated the radio image.

Two years after the eruption of V959 Monocerotis, the wind

### Box 3. Dust in novae

Nova ejecta have warm (10 000 K), hot (greater than 10 million K), and cold phases (1000 K). About 20% of all novae show dips in their optical light curves and an associated excess in the IR. Those properties are evidence of the transient creation of dust along our line of sight, dust that absorbs much of the visible light from the novae and reradiates the energy in the IR. Other novae show IR excess but no optical dips. That situation can be explained by dust that is out of our line of sight, perhaps because dust is preferentially formed near the orbital plane of the host binary. Stony Brook University's Spectral Atlas of Southern Novae database[17] contains example light curves of each. For dust grains to form and grow, the ejecta must be cold and relatively dense. Dust formation may be the consequence of the same shocks used to explain $\gamma$-ray emission from novae. Dust grains would be difficult to form without the high-density regions created by novae.[18]

emission faded and revealed an equatorial torus. The rendition in figure 4 shows the ejecta elongated in the north–south direction. In higher angular-resolution images, only the nonthermal emission from compact regions at the interface between the slow torus and the fast wind can be seen, which suggests that the $\gamma$-ray-producing shocks developed at that interface. It seems plausible that all novae share the torus and cone structure, and we have been using that framework as the working hypothesis to explain the particle acceleration in novae.

## Shocks raise new questions

Where will nova research go? The *Fermi* $\gamma$-ray observatory and the upgrade of the VLA radio facility led to the discovery of powerful, particle-accelerating shocks in novae. Those shocks suggest potential solutions to long-standing nova mysteries, such as the clumpiness of the ejecta, dust formation (see box 3), bizarre variations in optical-brightness patterns, and observed equatorial torus and bipolar morphologies. But powerful shocks also raise new questions. Why does the TNR lead to multiple, distinct flows that collide? Can the way in which those outflows are established help explain the large white-dwarf masses found in some interacting binary stars or shed light on what fraction of accreting white dwarfs could become type Ia supernovae? Where are the thermal signatures of the powerful shocks?

One near-future development that will help address those questions is determining accurate distances to novae using data from the European Space Agency's *Gaia* mission. Upcoming time-domain surveys will also uncover novae more efficiently. The next generation of x-ray observatories, including the High-Energy X-Ray Probe (HEX-P), a potential successor to *NuSTAR*, will be capable of diagnosing more shocks even closer to the time of their formation. Future radio telescopes will have higher sensitivity and higher angular resolution to capture the morphology of expanding nova ejecta in greater detail. Those observatories and other new astronomical facilities of the next decade will provide more answers and probably even more questions.

## REFERENCES


1. A. W. Shafter, *Astrophys. J.* **834**, 196 (2017).
2. M. Henze et al., *Astron. Astrophys.* **563**, A2 (2014).
3. M. J. Darnley et al., *Astron. Astrophys.* **563**, L9 (2014).
4. J. P. Osborne, *J. High Energy Astrophys.* **7**, 117 (2015).
5. R. M. Hjellming, in *Radio Emission from the Stars and the Sun: A Conference Held at the University of Barcelona, Barcelona, Spain 3–7 July 1995*, A. R. Taylor, J. M. Paredes, eds., Astronomical Society of the Pacific (1996), p. 174.
6. T. Nelson et al., *Astrophys. J.* **785**, 78 (2014).
7. Fermi–LAT collaboration, *Science* **329**, 817 (2010).
8. V. Tatischeff, M. Hernanz, *Astrophys. J. Lett.* **663**, L101 (2007).
9. B. D. Metzger et al., *Mon. Not. R. Astron. Soc.* **450**, 2739 (2015).
10. K.-L. Li et al., *Nat. Astron.* **1**, 697 (2017).
11. T. Nelson et al., *Astrophys. J.* **872**, 86 (2019).
12. H. M. Lloyd, T. J. O'Brien, M. F. Bode, *Mon. Not. R. Astron. Soc.* **284**, 137 (1997).
13. L. Chomiuk et al., *Nature* **514**, 339 (2014).
14. J. H. S. Weston et al., *Mon Not. R. Astron. Soc.* **457**, 887 (2016).
15. J. E. Naya et al., *Nature* **384**, 44 (1996).
16. A. Tajitsu et al., *Nature* **518**, 381 (2015).
17. F. M. Walter et al., *Publ. Astron. Soc. Pac.* **124**, 1057 (2012).
18. A. M. Derdzinski, B. D. Metzger, D. Lazzati, *Mon. Not. R. Astron. Soc.* **469**, 1314 (2017). PT