AstroTalk: Behind the news headlines of September 2016

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The star that didn't blow up after all

Between 1838 and 1845, astronomers surveying the night sky in the Southern Hemisphere noticed something strange. A previously inconspicuous star called η (eta) Carinae grew brighter and brighter, eventually outshining all other stars except Sirius, before it faded from view 20 years later. As part of this event, which astronomers call the 'Great Eruption,' a gaseous shell containing at least 10 and perhaps as much as 40 times the Sun's mass was shot into space. This material forms an hourglass-shaped, dust-filled cloud known as the Homunculus Nebula, which is now about a light-year long and continues to expand at more than 2.1 million kilometres per hour.

What had happened to cause this outburst? Did 19th Century astronomers witness some strange type of supernova, a star ending its life in a cataclysmic explosion?

> "*Not quite*," says Megan Kiminki, a PhD student at the University of Arizona (USA). "*η Carinae is what we call a supernova impostor. The star became very bright as it blew off a lot of material, but it was still there*."

Scientists call these outbursts supernova 'impostor' events, because they appear similar to supernovae but stop just short of destroying their star. Indeed, in the mid-20th Century, η Carinae began to brighten again.

By carefully analysing images of η Carinae taken with the *Hubble Space Telescope*, Kiminki and her team were surprised to discover that the Great Eruption was only the latest in a series of massive outbursts launched by the star system since the 13th Century. For scientists trying to piece together what makes star systems such as η Carinae tick, the findings are like the stereotypical smoking gun in a detective story.

> "*From the first reports of its 19th Century outburst up to the most recent data obtained with advanced capabilities on modern telescopes, η Carinae continues to baffle us*," says Nathan Smith, a faculty member also at the University of Arizona. "*The most important unsolved problem has always been the underlying cause of its eruption, and now we find that there were multiple previous eruptions. This is a bit like reconstructing the eruption history of a volcano by discovering ancient lava flows*."

Although the glowing gases of the Homunculus Nebula prevent astronomers from getting a clear look at what's inside, they have figured out that η Carinae is a binary system of two very massive stars that orbit each other every 5½ years. Both are much bigger than our Sun and at least one of them is nearing the end of its life.

"*These are very large stars that appear very volatile, even when they're not blowing off nebulae*," Kiminki says. "*They have a dense core and very fluffy envelopes. If you replaced our Sun by the larger of the two, which has about 90–100 solar masses, it could very well extend into the orbit of Mars*."

The larger of the two stars in the *η* Carinae system is a huge and unstable star that is nearing the end of its life, and the event that the 19th Century astronomers observed was a stellar near-death experience.

Because the Homunculus Nebula is such an iconic and visually stunning object, it has been a popular target of astronomical observations. A total of eight images, taken over the course of two decades with *Hubble*, turned out to be a treasure trove for Kiminki and her colleagues.

The original goal of the team's observing programme was to measure "proper motions" (motions across the sky as seen from Earth) of stars and protostellar jets—fast streams of matter ejected by young stars during their formation—in the Carina Nebula, but the same data also provided a powerful way to measure the motion of debris ejected by *η* Carinae itself.

"*As I was aligning the images, I noticed that the one that η Carinae in it was more difficult to align*," Kiminki says. "*We can only use objects as alignment points that aren't moving, and I thought, 'Wow, a lot of this stuff is really moving.' And then we decided to take a closer look*."

By aligning the multi-epoch images of the nebula, the team was able to track the movement of more than 800 blobs of gas *η* Carinae had ejected over time and derived a likely ejection date for each. The analysis showed that the Homunculus Nebula and the observed 19th Century brightening tell only part of the story. Measuring the speed with which wisps of ejected material expand outward into space revealed that they must have resulted from two separate eruptions that occurred about 600 and 300 years before the Great Eruption.

In addition to having a separate origin in time, the older material also showed a very different geometry from the Homunculus Nebula, where material was ejected out from the star's poles and appears symmetric about its rotation axis.

"*We found one of the prior eruptions was similarly symmetric, but at a totally different angle from the axis of the Great Eruption*," Kiminki explains. "*Even more surprising was that the oldest eruption was very one-sided, suggesting two stars were involved, because it would be very unlikely for one star to blow material out toward just one side*."

Although perplexing, the findings are a big step forward for astronomers trying to understand what causes the frequent outbursts.

"*We don't really know what's going on with η Carinae*," Kiminki says. "*But knowing that η Carinae erupted at least three times tells us that whatever* *causes those eruptions must be a recurring process, because it wouldn't be very likely that each eruption is caused by a different mechanism*."

"*Even though we still have not figured out the underlying physical mechanism that caused the 19th Century eruption, we now know that it isn't a one-time event*," Smith says. "*That makes it harder to understand, but it is also a critical piece of the puzzle of how very massive stars die. Stars like η Carinae apparently refuse to go quietly into the night*."

η Carinae's eruptions provide unique insights into the last unstable phases of a very massive star's life. Researchers who study supernovae have identified a subclass of supernova explosions that appear to suffer violent eruptions shortly before they finally explode. Smith notes that *η* Carinae might be our nearest example of this.

η Carinae is one of the closest stars to Earth that is likely to explode in a supernova in the relatively near future (although on astronomical timescales, the 'near future' could still be a 100,000 years away, or even longer). When it does, expect an impressive view from Earth, far brighter still than its last outburst: SN 2006gy, the brightest supernova ever observed, came from a star of the same type, although from a galaxy over 200 million light-years away.

Meanwhile, an independent team of astronomers has created the first high-resolution three-dimensional model of the expanding cloud produced by the outburst.

"*Our model indicates that this vast shell of gas and dust has a more complex origin than is generally assumed*," said Thomas Madura at NASA's Goddard Space Flight Center in Greenbelt, Maryland (USA). "*For the first time, we see evidence suggesting that intense interactions between the stars in the central binary played a significant role in sculpting the nebula we see today*."

Using the European Southern Observatory's Very Large Telescope, the team imaged near-infrared, visible and ultraviolet wavelengths along 92 separate swaths across the nebula, making the most complete spectral map to date. The researchers used the spatial and velocity information provided by these data to create the first high-resolution, fully 3D model of the Homunculus Nebula.

The shape model was developed using only a single emission line of near-infrared light, emitted by molecular hydrogen gas. The characteristic 2.12 μm light shifts in wavelength slightly, depending on the speed and direction of the expanding gas, allowing the team to probe even dust-obscured portions of the Homunculus Nebula that face away from Earth.

The new shape model confirms several features identified by previous studies, including pronounced holes located at the ends of each lobe and the absence of any extended molecular hydrogen emission from a dust skirt apparent in visible light near the centre of the nebula. New features include curious arm-like protrusions emanating from each lobe near the dust skirt, vast, deep trenches curving along each lobe, and irregular extensions on the side facing away from Earth.

> "*One of the questions we set out to answer with this study is whether the Homunculus contains any imprint of the star's binary nature, since previous efforts to explain its shape have assumed that both lobes were more or less identical and symmetric around their long axis*," explained team member Jose Groh, an astronomer at Geneva University in Switzerland. "*The new features strongly suggest that interactions between η Carinae's stars helped mold the Homunculus*."

Turning our attention now to results from another of the great space observatories that are currently orbiting the Earth, as one of the first objects observed by the *Chandra X-ray Observatory* after its launch some 17 years ago, the *η* Carinae system also continues to reveal new clues about its nature through the X-rays it generates.

Astronomers are trying to learn more about the two stars in the *η* Carinae system and how they interact with each other. The more massive of the two stars is quickly losing mass through a wind streaming away from its surface at over a million kilometres per hour. While not the giant purge of the Great Eruption, this star is still losing mass at a very high rate that will add up to the Sun's mass in about a millennium.

Although smaller than its partner, the companion star in *η* Carinae is also massive, weighing in at about 30 times the mass of the Sun. It is losing matter at a rate that is about a hundred times lower than its partner, but this is still a prodigious weight loss compared to most other stars. The companion star beats the bigger star in wind speed, with its wind clocking in almost ten times faster.

When these two speedy and powerful winds collide, they form a bow shock – similar to the sonic boom from a supersonic airplane – that then heats the gas between the stars. The temperature of the gas reaches about ten million degrees, producing X-rays that *Chandra* can detect. At their closest approach, the faster wind from the smaller star carves a tunnel through the denser wind of its companion. The opening angle of this cavity closely matches the length of the trenches (130 degrees) and the angle between the arm-like protrusions (110 degrees), indicating that the Homunculus Nebula likely continues to carry an impression from a periastron interaction around the time of the Great Eruption.

The *Chandra* image of *η* Carinae shows low-energy X-rays in red, medium-energy X-rays in green, and high-energy X-rays in blue. Most of the emission comes from low- and high-energy X-rays. The blue point source is generated by the colliding winds, and the diffuse blue emission is produced when the material that was purged during the Great Eruption reflects these X-rays. The low-energy X-rays further out show where the winds from the two stars, or perhaps material from the Great Eruption, are striking surrounding material. This surrounding material might consist of gas that was ejected before the Great Eruption.

An interesting feature of the η Carinae system is that the two stars travel around each other along highly elliptical paths during their 5½ year orbit. Depending on where each star is on its oval-shaped trajectory, the distance between the two stars changes by a factor of twenty. These oval-shaped trajectories give astronomers a chance to study what happens to the winds from these stars when they collide at different distances from one another.

Throughout most of the system's orbit, the X-rays are stronger at the apex, the region where the winds collide head-on. However, when the two stars are at their closest during their orbit—a point astronomers call 'periastron'—the X-ray emission dips unexpectedly. At periastron, the immense and brilliant stars of η Carinae are only as far apart as the average distance between Mars and the Sun.

To understand the cause of the X-ray dip near periastron, astronomers observed η Carinae with *Chandra*. The results provided the first detailed picture of X-ray emission from the colliding winds in η Carinae. The study suggests that part of the reason for the dip at periastron is that X-rays from the apex are blocked by the dense wind from the more massive star in η Carinae, or perhaps by the surface of the star itself. Another factor responsible for the X-ray dip is that the shock wave appears to be disrupted near periastron, possibly because of faster cooling of the gas due to increased density, and/or a decrease in the strength of the companion star's wind because of extra ultraviolet radiation from the massive star reaching it.

Because it takes light 7,000 years to travel from η Carinae to Earth, much could have happened in the meantime. "*η Carinae may have gone supernova by now, and we wouldn't know until 7,000 years from now*," Kiminki said.

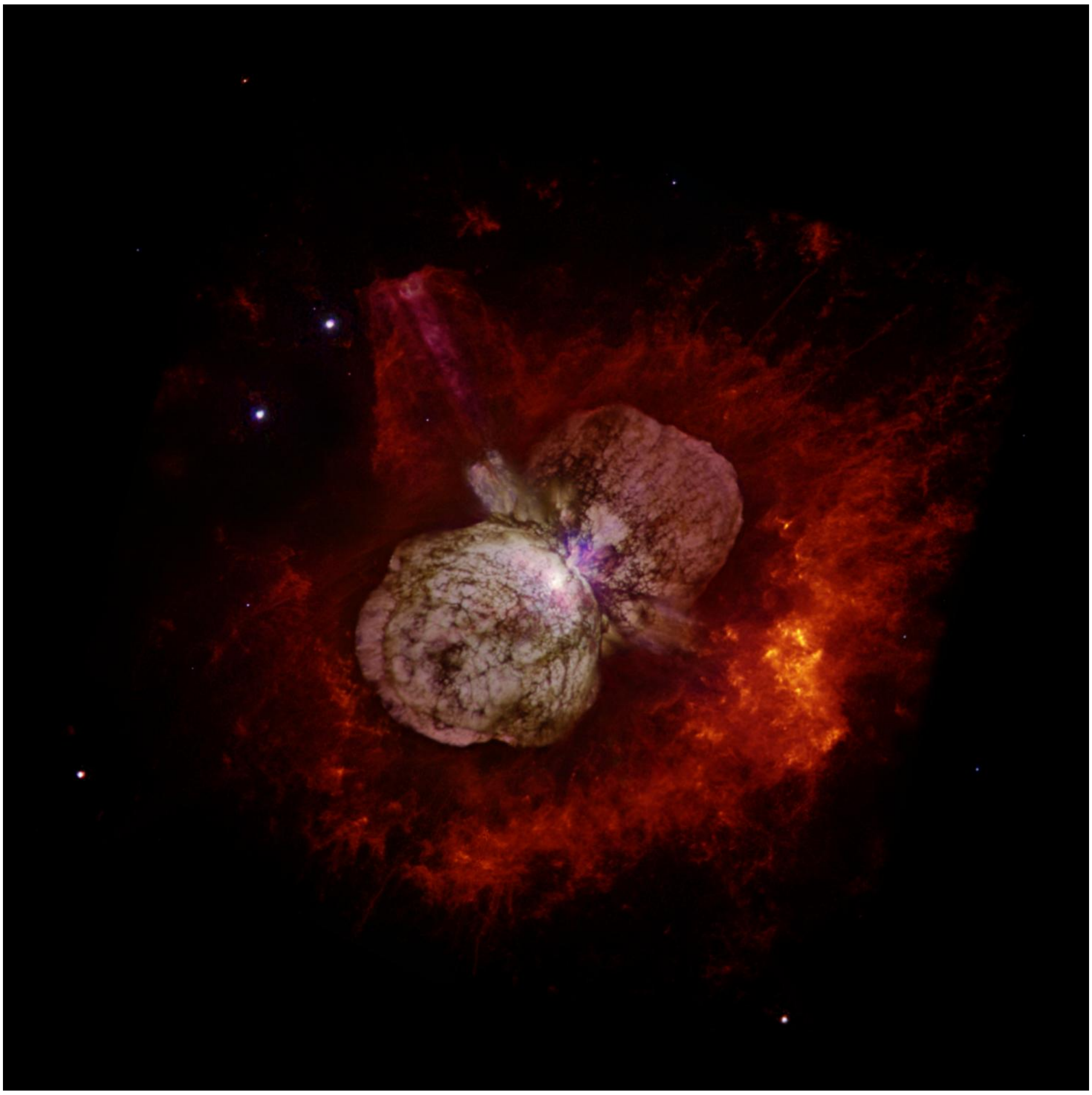

Figure 1: Best known for an enormous eruption in the 1840s that created the billowing, hourglass-shaped Homunculus Nebula imaged here by the *Hubble Space Telescope*, η Carinae is the most massive and luminous star system within 10,000 light-years. (*Credit: Nathan Smith/University of Arizona and NASA*)

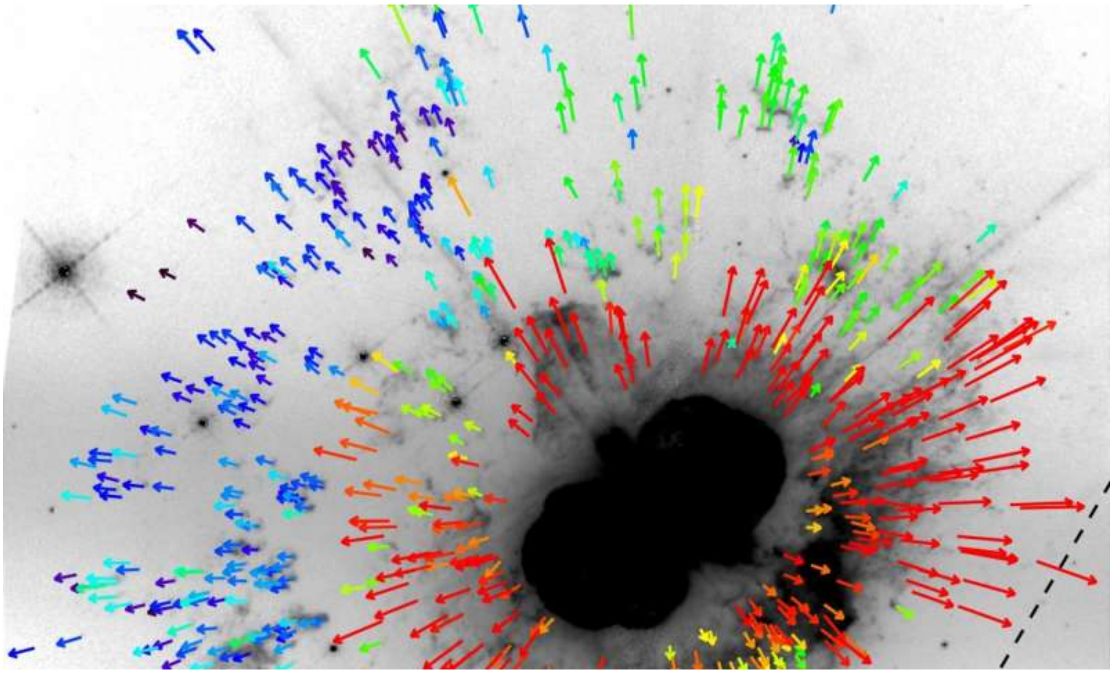

Figure 2: Arrows illustrating the observed proper motions of 792 features in the ejecta of η Carinae. The arrows are color-coded by the date of ejection from the central star. Until now, only one eruption was known (red arrows). Blue and green arrows mark previous eruptions (mid-13th and mid-16th Centuries, respectively). (*Credit: Kiminki et al./NASA*)

Figure 3: Preview of a supernova. (*Credit: NASA/ESA*)

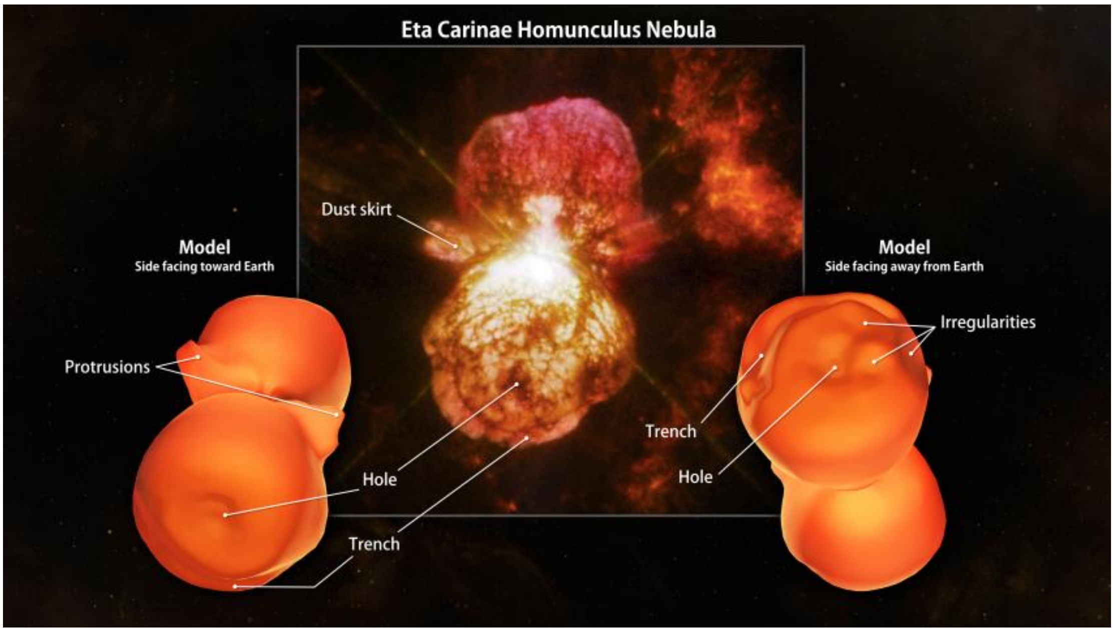

Figure 4: A new shape model of the Homunculus Nebula reveals protrusions, trenches, holes and irregularities in its molecular hydrogen emission. The protrusions appear near a dust skirt seen at the nebula's centre in visible light (inset) but not found in this study, so they constitute different structures. (*Credit: NASA Goddard; inset: NASA, ESA, Hubble SM4 ERO Team*)

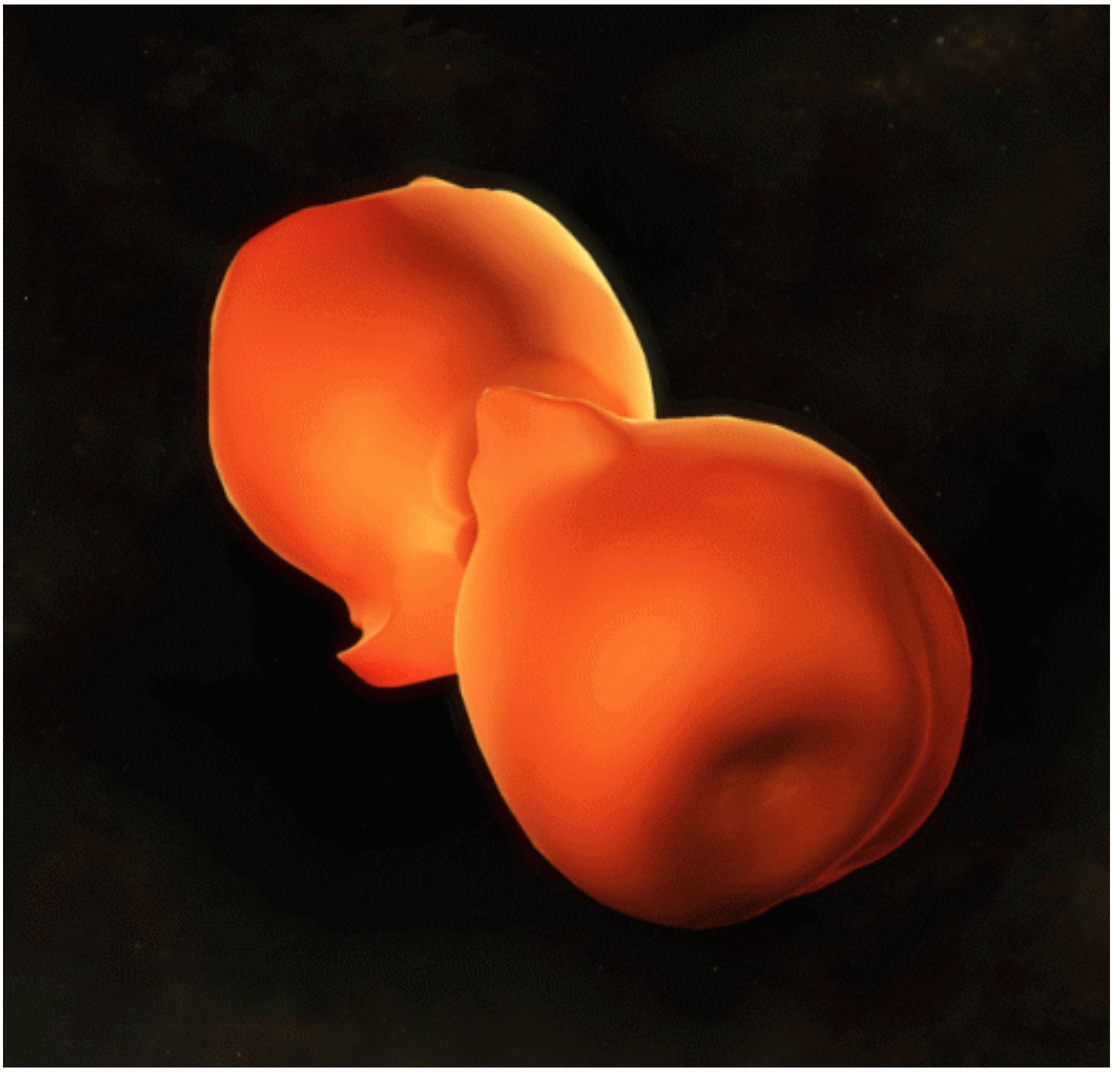

Figure 5: 3D Homunculus Nebula model. (*Credit: NASA Goddard's Conceptual Image Lab*)

Figure 6: Chandra X-ray image of η Carinae. (*Credit: NASA/CXC/GSFC/K.Hamaguchi et al.*)

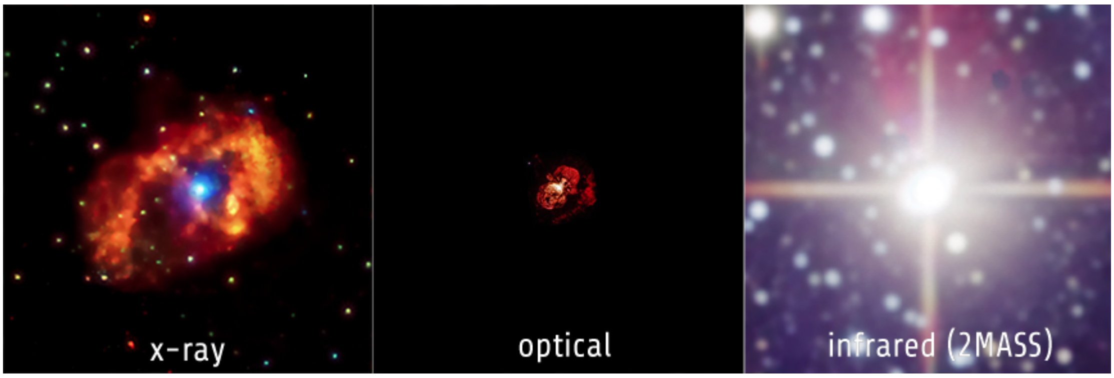

Figure 7: This multi-panel image shows η Carinae in the same field of view using three different telescopes. From left to right, the images are from the *Chandra X-ray Observatory*, the *Hubble Space Telescope* in optical light, with the ground-based 2MASS survey in infrared. The X-ray image reveals an outer horseshoe-shaped ring, a hot inner core, and a hot central source. The optical image shows two giant bubbles expanding away from the centre of the system at over a million kilometres per hour. The infrared data reveal that η Carinae is one of the most luminous systems in the Milky Way. (*Credit: Optical: NASA/STScI, Near-Infrared: 2MASS/UMass/IPAC-Caltech/NASA/NSF*)