

Neighboring stars shaped a planetary nebula

Early images from the *JWST* reveal previously unseen fingerprints of stellar interactions with a dying star.

On 12 July 2022, NASA released the first images from the *James Webb Space Telescope* (*JWST*). Chosen to demonstrate the telescope's capabilities, the five results included a distant galaxy cluster, an atmospheric spectrum of a distant planet, a quintet of galaxies, a stellar nursery, and the one Orsola De Marco was most excited about: NGC 3132, a planetary nebula (PN) informally called the Southern Ring Nebula. De Marco, of Macquarie University in Sydney, Australia, stayed awake late to watch the announcement broadcast from Maryland. As soon as she saw the new PN image, she noticed something unexpected, and before the announcement was over, De Marco and her colleagues in the PN research community were exchanging emails about the puzzling result.

A PN is the end stage of an intermediate-mass star, and such nebulae are the biggest carbon and nitrogen producers in the universe. The glowing shells of ionized gas form when a star of 1–8 solar masses dies. A dying star expands, and the outermost material escapes more easily. The star eventually loses enough mass to reveal its hot core, which, no longer burning, becomes a white dwarf. The star temporarily emits

UV radiation, which ionizes the cast-off gas and creates the characteristic glow. The PN stops glowing once the star dims too much to emit enough UV radiation.

The Southern Ring Nebula, which is about 2500 light-years from Earth, formed from a dying star of about 3 solar masses. It had already been imaged by the *Hubble Space Telescope* and various ground-based observatories. The *JWST* image in the near-IR, shown in figure 1a, resembles previous observations, which have largely been in the visible and near-IR. The initial surprise came from the *JWST*'s mid-IR image, seen in figure 1b. A red dot near the center of the nebula shows the dying star brightly shining in the IR. The star is still quite hot—around 130 000 K. At that temperature, it should emit blue or UV light. Where was the IR coming from?

De Marco and 68 colleagues from around the world figured out the answer to that question and the origins of several other curious features of the Southern Ring Nebula.¹ The astrophysics detectives identified evidence of unseen stars and pieced together how those stars shaped the nebula. Their study contributes to an open question about how PNs form and evolve.

Dusting for fingerprints

PNs have nothing to do with planets. The “planetary” in the name is a hold-over from the 18th century when William Herschel noted that a PN's round shape and uniform color—as seen through telescopes of the time, anyway—resembled a planet. Since then, improved observational tools have revealed that PNs are far from uniform and take various shapes. Around 10–20% have the spherical form that would be intuitively predicted for a spherical star expelling a spherical wind.²

Over the past 20 years, researchers have suspected that to get the non-spherical PN shapes seen in the sky, the dying star must interact with a neighboring star. They have looked for evidence of binary stars at the heart of PNs, but directly observing them can be difficult when the companion star is too dim or too close to the brighter central one to be detected. Indirect signatures, however, have suggested that a large fraction of PNs have close companion stars.

Astronomers already knew that the Southern Ring Nebula was at least a binary star system. The PN's bright star in near-IR (see figure 1a) and visible images is not the one that formed the PN, even though it appears near the center, but rather a companion star threefold the

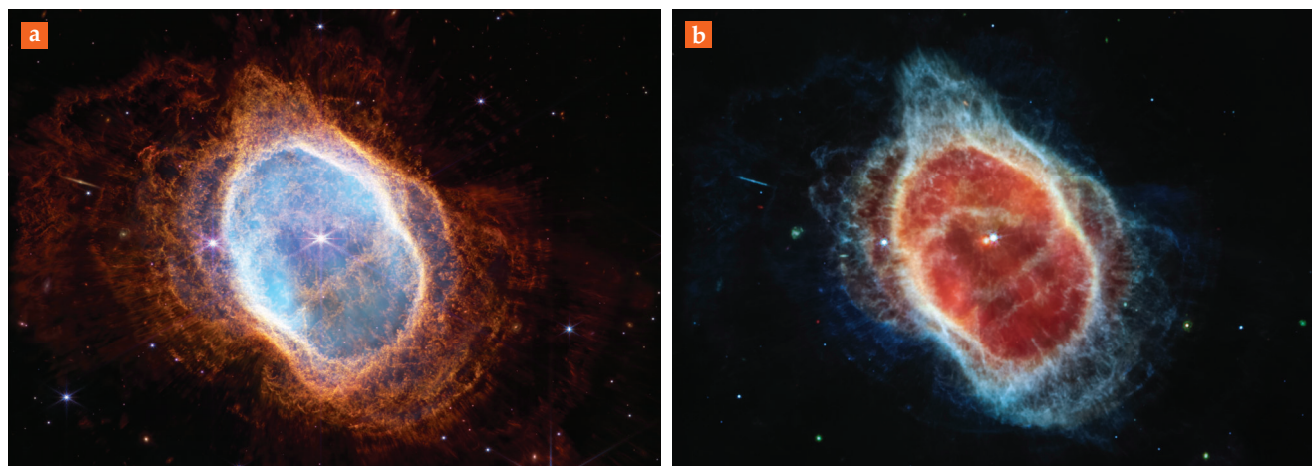


FIGURE 1. PLANETARY NEBULAE are glowing shells of gas that form around intermediate-mass dying stars. The one shown here—NGC 3132, or the Southern Ring Nebula—was among the early objects imaged by the *James Webb Space Telescope*. **(a)** The near-IR image resembles earlier ones taken by other telescopes, although the increased light collection reveals a pattern of incomplete concentric rings (most noticeable in the lower right quadrant) in the outermost gas. **(b)** The mid-IR image surprised astronomers because the dying star, the red center dot, wasn't expected to emit in the IR. (Courtesy of NASA/ESA/CSA/STScI.)

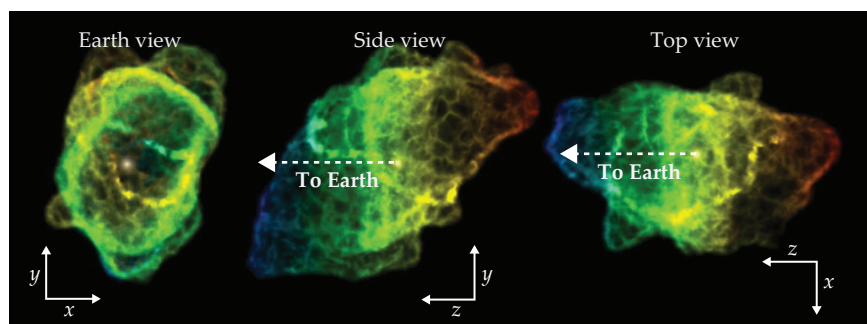


FIGURE 2. A RECONSTRUCTION of the Southern Ring Nebula's ionized gas bubble, shown here at different orientations, clarifies the nebula's structure and how it relates to stellar interactions. The roughly egg-shaped nebula features bumps that come in pairs on opposite sides. From simulations, researchers propose that the bumps are from pairs of plasma jets ejected by two stars near the dying star. From the bumps and other evidence, they deduce that the nebula's center hosts four or five stars. The colors here show the Doppler shift of the light that reaches Earth. (Adapted from ref. 1.)

mass of the Sun. In 1999 *Hubble* just made out the PN's faint dying star next to the bright companion. The two stars are too far apart to interact in any substantial way, however, so that visible companion couldn't be responsible for the shape of the nebula. Or for the unexpected IR emission.

"When something is shining in the IR, it has to be relatively cool, and in this case, it has to be dust," says De Marco. Dust around a central star warms just enough to emit in the mid-IR or burns away. Typically a hot star at a PN center ends up surrounded by a dusty disk because of a strong interaction with a nearby star.

The researchers concluded that at some point, the dying star that made the Southern Ring Nebula had a close neighbor strip away some of its mass and leave behind dust. As a result, in the mid-IR image shown in figure 1b, the dying star shows up as a distinct red dot near the PN's center, with its previously known distant companion appearing as the bluish-white dot next to it. The close dust-producing companion may still be there, but it's too dim to see, or it may have merged with the dying star.

Bump in the night

The *JWST*'s look into the mid-IR had thus revealed unexpected dust. "IR observations tend to be a little rarer" than those in the visible, says De Marco. "Whenever you open that window, there are always surprises." The dust was the first of several such surprises enabled by the *JWST*. As the largest space telescope, it captures more photons and picks up fainter features than previous instruments. One such fea-

ture is the pattern, albeit weathered and incomplete, of concentric rings formed by the outermost gas of the Southern Ring Nebula, just visible in figure 1a. "In planetary nebulae, there's a long history of studying rings like those," says De Marco. "The best explanation is that when the nebulae form and slowly puff out, the gas goes past whatever is in the way. And if the dying star has a companion that goes around it, the companion stirs the gas and creates an imprint of a spiral." As the spiral expands, it forms rings.

Researchers already knew how quickly a PN's gas expands, usually around 20 km/s. So Shazrene Mohamed of the University of Cape Town, South Africa, modeled how far the stirring star is from the dying one through the distance between rings—effectively the companion star's orbital period. She found a distance of 40–60 AU, which is farther than the neighbor responsible for the dust and much closer than the visible companion. So the tally increased to four stars: the dying one; the distant, previously known one; the close, dust-producing one; and now a middle-distance, ring-producing one. "We've got a quartet," says De Marco, "and though indirect, the evidence is pretty strong" because it's based on long-standing models for nebulae and binary interactions.

More-tenuous evidence points to a possible fifth star. A three-dimensional reconstruction of the PN ionized gas bubble, shown in figure 2, was generated by Wolfgang Steffen and his company, Ilumbra, which models astronomical objects. The researchers 3D-printed the final fit. As they held the object, which was roughly egg-shaped with many bumps, they no-

ticed the bumps came in pairs on opposite sides, and the lines between the pairs went roughly through the center star. A likely way to produce such bumps is plasma jets, which come in pairs, that originate near the dying star. The number and diverse orientations of the jets required to account for the PN bumps are possible only from interactions between three stars. So in addition to the close companion responsible for the dust, there may be another star that's closer than the ring-producing or visible companion. A five-star system is unusual but not impossible. For stars the mass of the dying one, models predict around 10% have four companions.

The game is afoot

The researchers compare their work to a murder investigation: A neighboring star that contributes to and expedites the central star's death murders it, effectively. To do so, the companion needs to be close enough to interact strongly and pull away mass. The visible companion is thus an innocent bystander, and the one that made the rings is an accomplice but didn't strike the lethal blow. The one or two closest companions are the murderers.

The investigation hinged on the wavelength range, improved resolution, and greater light collection provided by the *JWST*. (See "First observations test *JWST* capabilities," *PHYSICS TODAY* online, 17 November 2022.) "Indirect evidence is always difficult to deal with, and if it's indirect and fuzzy, it's even harder," says De Marco. "But when the indirect evidence is sharp, it becomes useful." In the future, similar analyses could be done on additional PNs with varied shapes—for example, the Cat's Eye Nebula, whose name evokes its complicated and unusual structure.

"With the Southern Ring Nebula, we have a superb example of a complex form that is not very different from many other nonspherical planetary nebulae," says George Jacoby of NOIRLab. "But now with sufficient data to derive an excellent set of models and explanations for those complexities, we can be much more confident generalizing the physics of those planetary nebulae."

Heather M. Hill

References

1. O. De Marco et al., *Nat. Astron.* **6**, 1421 (2022).
2. G. H. Jacoby et al., *Publ. Astron. Soc. Aust.* **27**, 156 (2010).