How the Sun will die

When Sun-like stars exhaust their fuel, they cast off shells of gas, creating colorful fireworks. **by Bruce Balick**

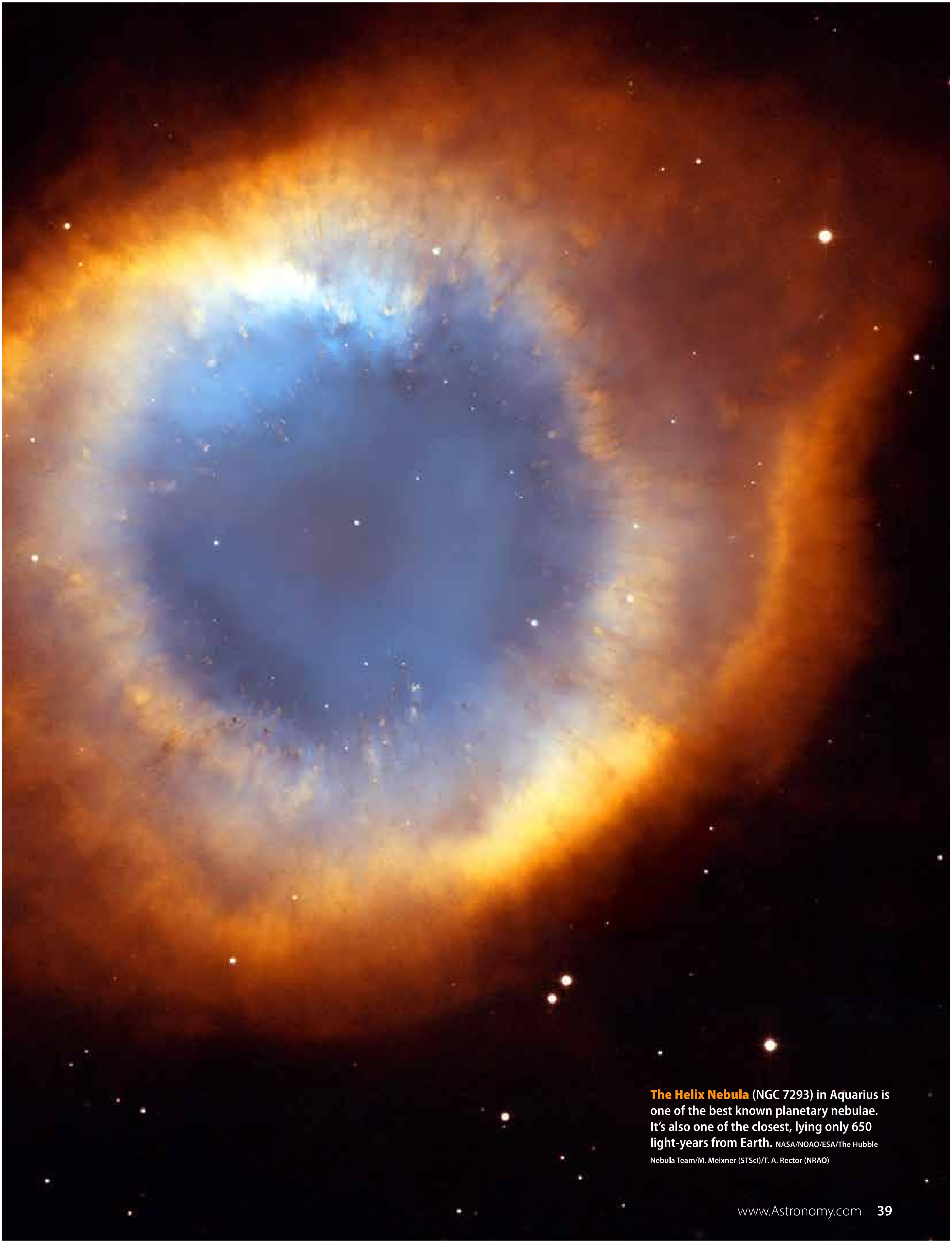
Our Sun has lived half its life. Five billion years from now, its inner workings will trigger a transformation. For a brief span, distant observers will not see a star, but a colorful, expanding cloud of gas called a planetary nebula.

Astronomers pay close attention to planetary nebulae, and these objects have gotten more popular since the mid-1990s, when the Hubble Space Telescope began delivering spectacular photographs of them. In fact, a new planetary nebula has probably flared to life somewhere in the Milky Way since Hubble went into service. The object may be too far, too small, or too faint to detect, but it's out there waiting to return our gaze.

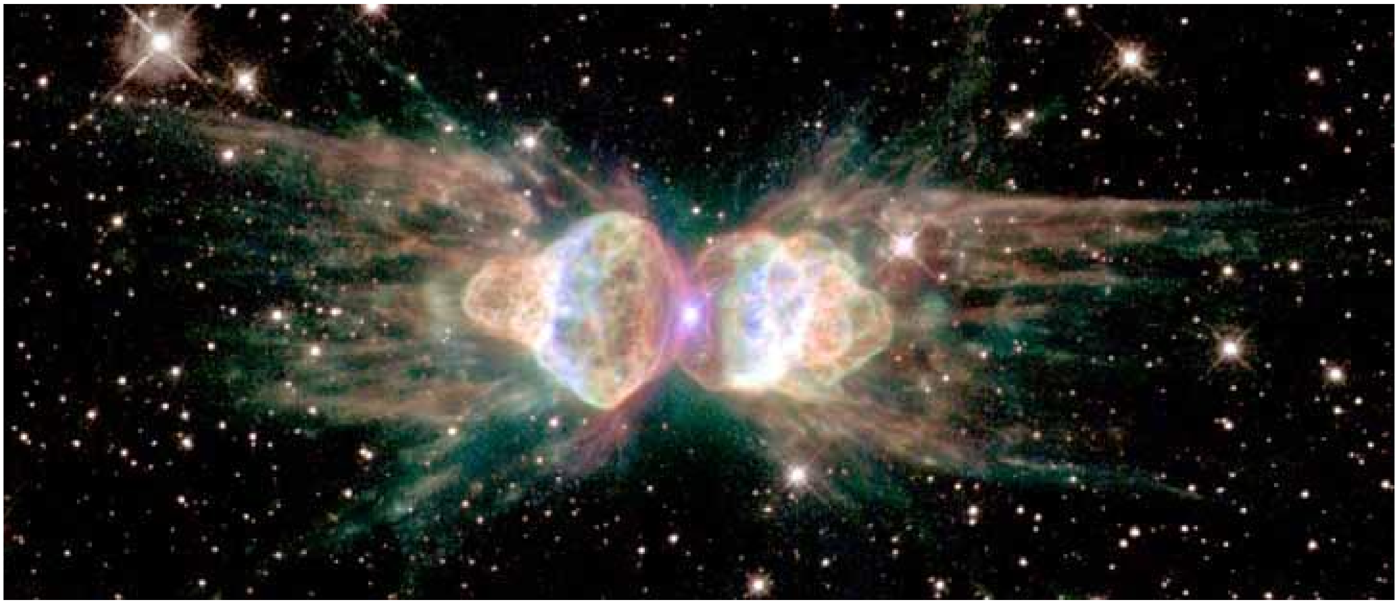
Despite the efforts of astronomers using Hubble and many other instruments that have probed planetary nebulae in every wavelength, there remain important aspects of these enigmatic objects we don't understand.

This infrared view of the Helix Nebula from NASA's Spitzer Space Telescope shows features called "cometary knots" with blue-green heads. The knots glow brightly — because of shock fronts or ultraviolet radiation — at wavelengths between 3.2 and 4.5 microns, to which astronomers assigned the colors blue and green, respectively. NASA/JPL-Caltech/J. Hora (Harvard-Smithsonian CfA)

Astronomy magazine © 2013 Kalmbach Publishing Co. This material may not be reproduced in any form without permission from the publisher. www.Astronomy.com



The Helix Nebula (NGC 7293) in Aquarius is one of the best known planetary nebulae. It's also one of the closest, lying only 650 light-years from Earth. NASA/NOAO/ESA/The Hubble Nebula Team/M. Meixner (STScI)/T. A. Rector (NRAO)



The Ant Nebula (Menzel 3) resembles a garden-variety ant. This Hubble image reveals the ant's body as a pair of fiery lobes protruding from a dying Sun-like star. The Ant Nebula lies in the southern constellation Norma approximately 3,000 light-years away. NASA/ESA/The Hubble Heritage Team (STScI/AURA)

The majority rules

The story of a planetary nebula starts at the end of a star's red giant phase. That's when the star's core finally dies. It becomes a dense, Earth-sized lump of carbon containing about 50 percent of the Sun's original mass. The core has no way to replenish its heat, so it cools like an ember in a fireplace.

Some life remains in the layers outside the core, however. Gravity has compressed shells of fresh hydrogen and helium to their thermonuclear fusion points. They burn furiously, but only briefly. For example, the Sun will be about 30 times brighter than now when it enters the red giant stage. At the most luminous stage of its evolution, however, it will be 150 times larger and 2,100 times more luminous than it is now.

Within stars that will become planetary nebulae, carbon is the ultimate fusion byproduct. Such a star's atmospheric carbon settles down and adds its mass to the inert carbon core. The remaining fuel is too far from the core, so not enough mass remains above it to compress it to its fusion point. Instead, the last spasmodic fits of helium "burning" — a colloquial term substituted for "fusion" by astronomers — fling these outer layers into space, resulting in a planetary nebula a thousand years later. Each of the spasmodic "sneezes" produces a new bubble of gas flowing outward at about 36,000 mph (58,000 km/h). Astronomers can see these bubbles as concentric rings of luminous gas in many Hubble images of planetary nebulae.

Bruce Balick *is Chairman of the Department of Astronomy at the University of Washington, Seattle. He serves on the design team for WFPC 3.*

This cosmic jellyfish actually is planetary nebula OH231.8+4.2, sometimes called the Rotten Egg Nebula. Shown in blue is light from hydrogen and ionized nitrogen arising from supersonic shocks where the gas stream collides with surrounding material. This image showed, for the first time, these complex gas structures predicted by theory. ESA/Valentin Bujarrabal (Observatorio Astronomico Nacional, Spain)

The star's final helium flash is a doozy. Instead of another bubble, we get a dense and highly organized spray of gas and fresh dust particles. This event creates the planetary nebula's shape — that is, its complex inner structure and organization. The "superwind" is too organized and symmetric to be the chaotic remnant of an explosion. Rather, there's method — or perhaps a few methods — in the mad out-rush of material.

In many planetary nebulae, the dark dust lane and the bright lobes seen in images along their major axes form in the final helium flash. This material cools as it expands. Based on observations, astronomers surmise dust particles quickly condense at the base of the outflow just before the gas disperses.

New dust makes up about 1 percent of the mass ejected into the interstellar medium. This enriches the surrounding area with carbon- and silicate-rich particles along with a variety of carbon-based molecules. The dust particles are small (0.001 millimeter or so) and reflect light from the nearby dying star.

The newly born preplanetary nebulae (sometimes called protoplanetary nebulae) are small and far away on average. Because they appear tiny, Hubble is the observing tool of choice.

Only the most elite of all stars — those whose mass puts them in the upper 1 percent — become supernovae. The rest settle for "15 minutes of fame" before they fade away, and we see the results as planetary nebulae. That time span — when the star ejects and ionizes its outer layers in a final fiery, smoky breath — is what attracts astronomers' attention.

Planetary nebulae ultimately expand and disperse into the ocean of galactic gas known as the interstellar medium. All that remains are ever-cooling white dwarfs — nature's burnt cherry pits — too faint to see after a billion years and too numerous to name.

Revealing a planetary

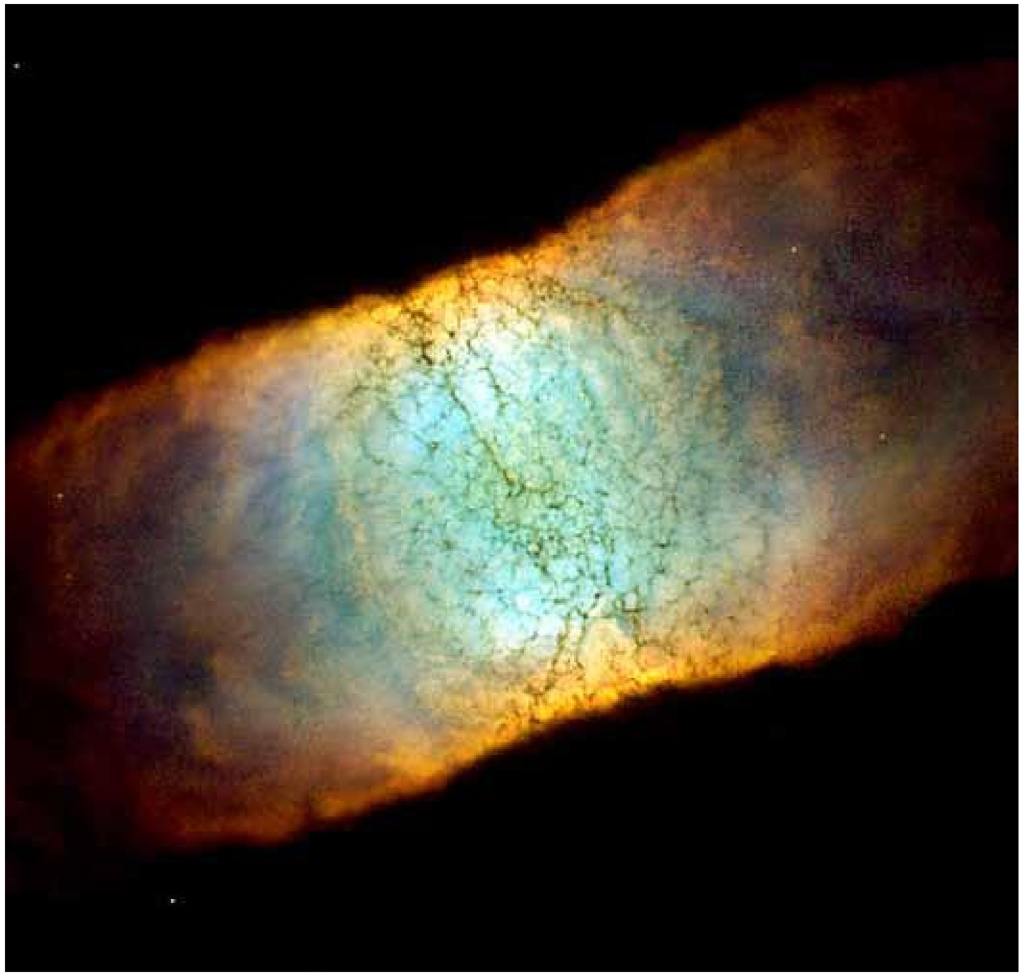
It takes about a thousand years for a new planetary nebula to become visible. Its gas has to expand to a size we can detect, and the star at its center must shed its cool outer layers and reach a temperature of about 30,000 kelvins (K).

Before this happens, the nascent planetary nebula shines only because its newly formed dust particles happen to reflect starlight in our direction. Indeed, the dust may hide the visible light entirely until the nebula expands for a while and light finds pathways out of the opaque cocoon.

At 30,000 K, ultraviolet photons start to strip electrons from neutral atoms. This ionizes the gas, rendering the planetary nebula visible. The object's spectrum shows lines of hydrogen, helium, and other elements. Using filters that isolate these emissions, Hubble and other telescopes can take the spectacular color images we've grown accustomed to.

No chain is stronger than its weakest link, and no theory of stellar evolution can be complete without understanding the origin of the shapes of planetary nebulae. It's a thrill for an observer like me to get imaging time on Hubble. However, there's a sobering — and, for the really spectacular nebulae, gut-wrenching — realization that we have not yet explained the structure of these amazing objects.

From a scientific viewpoint, images of preplanetary nebulae pose a problem. All known stellar wind acceleration mechanisms convert light energy from the star into outward motions of dust particles. Just like the Sun shining on a comet's tail, light pushes on the dust particles and forces them to flow outward. If the star is round, then the outflows also should look round. Almost none of the preplanetary nebulae behave this way, however.



The Retina Nebula (IC 4406) exhibits a high degree of symmetry; the left and right halves are nearly mirror images of each other. Gas and dust form a vast doughnut of material streaming outward from the dying star. One perplexing feature of IC 4406 is the irregular lattice of dark lanes that crisscross the nebula's center. We see them in silhouette because their density is 1,000 times greater than the rest of the nebula. NASA/The Hubble Heritage Team (STScI/AURA)/C. R. O'Dell (Vanderbilt Univ.)

The stellar superwind may be the last big event in a star's life, but there's more to come. Ultraviolet observations of the emerging star clearly show the presence of a "fast wind" whose speed is truly impressive — up to 350,000 mph (560,000 km/h) — but whose mass density is smaller than that of the superwind.

The fast wind quickly smashes into the slower wind ejected earlier, pushes the gas out of its way, and sears whatever gas it contacts. This effect creates the appearance of an empty cavity between the central star and the rest of the nebula. The cavity is no more empty than an inflated tire; it just looks that way.

Inside this illusionary cavity, we detect X rays from gas heated to a million degrees or more by the fast wind. At its perimeter, we find gas that has been scooped up into a thin rim. Beyond the rim lies a slow wind that has yet to sense the bubble's presence. Ultimately, the bubble pops when it reaches the outer edge of the slow wind, emptying its contents into the interstellar medium. As it does, it may scoop up much older gas the star had deposited when it was still a red giant. This can create large halos or pairs of bubble-like lobes.

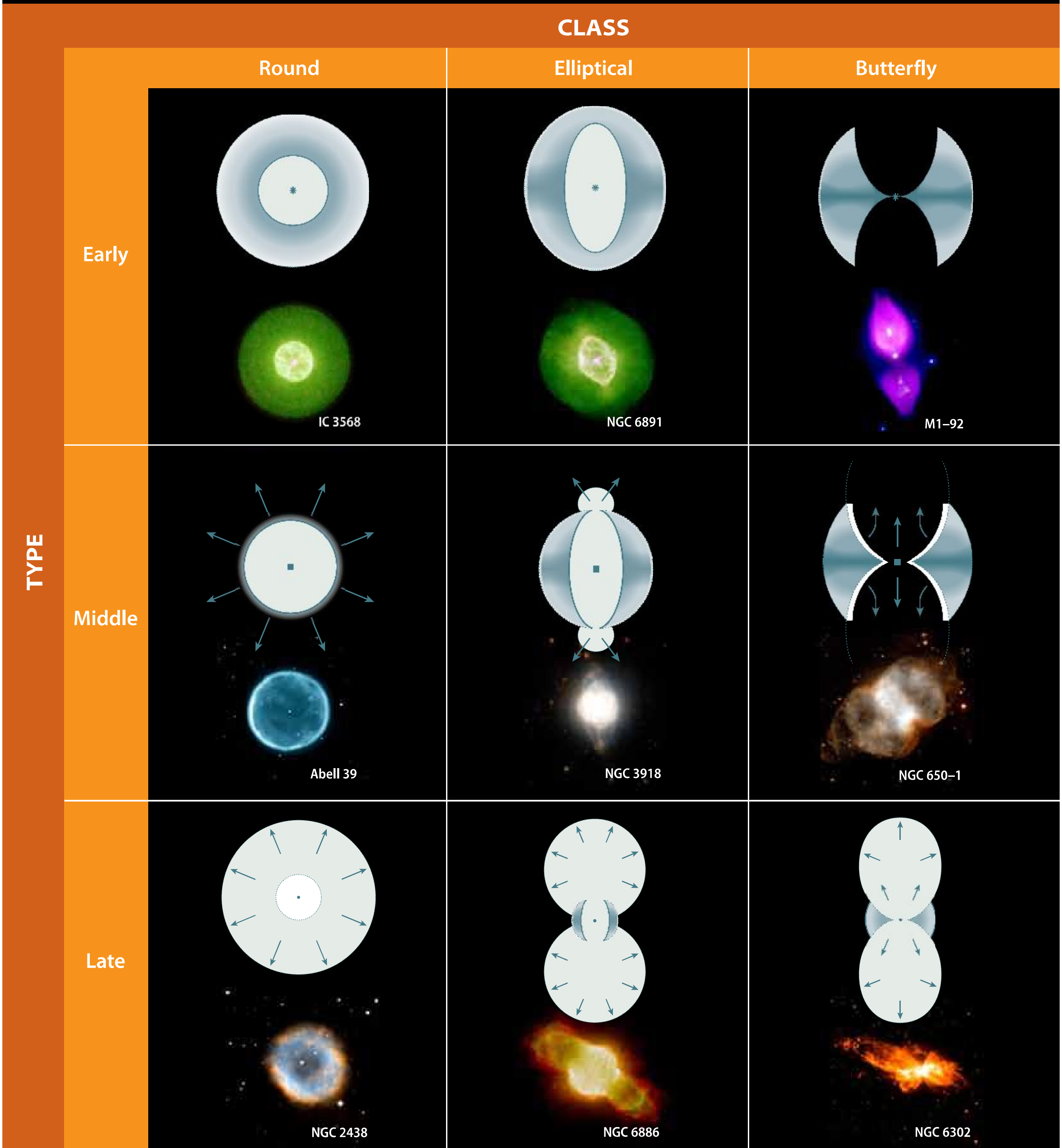
A planetary nebula "gets its certificate" when the central star becomes hot enough to ionize the preplanetary nebula.

Spanish radio astronomers uncovered a second problem in 2001. They measured the Doppler shifts from carbon monoxide (CO) emissions (CO is always a bountiful molecule in cool, dusty gas) and found the momentum of the outflowing gas is more than 10,000 times larger than light-pressure based acceleration mechanisms had predicted.

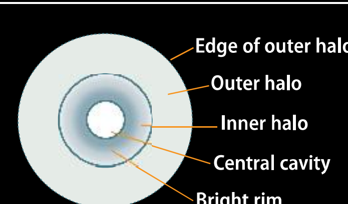
A planetary nebula "gets its certificate" when the central star becomes hot enough to ionize the preplanetary nebula. The fast wind peels away the star's cool outer layers and exposes hotter inner regions. So the star's surface becomes increasingly blue. This takes a few hundred to a few thousand years, after which the star's surface temperature reaches up to 100,000 K. For comparison, the Sun's surface is currently 5,800 K.

The small, hot surface of the dying star emits ultraviolet light before it starts

How astronomers classify planetary nebulae



Astronomers have identified three types of planetary nebulae, along with three classes. Combinations allow for nine distinct shapes among these objects. The key image to the right shows the nebulae's main parts. All planetary nebula images courtesy of NASA/ESA/STScI; artwork: *Astronomy*: Roen Kelly after Bruce Balick



to cool and fade away. The radiation strips electrons from atoms in the nebula. Suddenly, the nebula fluoresces and becomes easy to observe. The object's luminosity rises abruptly. Instead of reflecting a small portion of the star's total light, the nebula converts about half of the radiation into visible light. This brightening, coupled with their longer lifetimes and ever-growing diameters, make most planetary nebulae much easier to find than preplanetary nebulae.

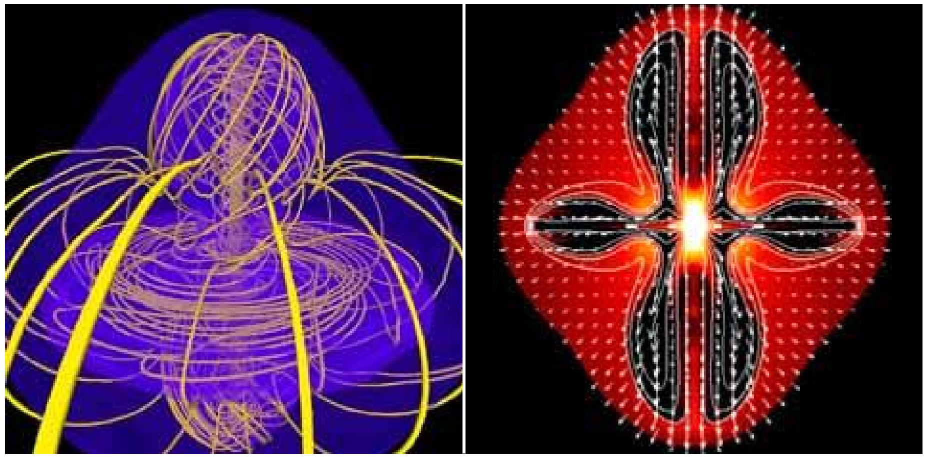
Back to the puzzle board

The success of the first models of planetary nebulae elated astronomers in the 1990s, but it didn't last long. As Hubble produced more images, the complexity of the structures soon led to humility. We've made a good start, but the quest to understand the shapes of planetary nebulae continues. Of particular interest are the small knots, which don't readily form in the lovely, regular patterns. Another area of interest is planetary nebulae with more than one symmetry axis. And then there's the question of shapes.

The same shapes appear for planetary nebulae as for preplanetary nebulae — round, elliptical, and butterfly. However, half of the preplanetary nebulae are ellipticals with dust lanes cutting through their centers. For planetary nebulae, only 10 percent are bipolar, and none show dust lanes. Something happens to morph or distort their shapes, providing astronomers another challenge. Astronomers also wonder why planetary nebulae have such a narrow range of shapes.

The shapes are also strikingly symmetrical. One popular idea is that a companion star exerts a gravitational tug on the loosely bound outer layers of a red giant star, or perhaps the giant swallows its companion when it starts to bloat.

In the former case, the tidal forces on the outer layers drag them toward the rapidly orbiting companion star for the duration of the final helium flash. However, by the time the giant's material reaches the companion, it has moved on. So most of the material just keeps going outward in a spiral pattern, like water from a sprinkler. This forms a tightly wound one-armed spiral in a thin disk. Moreover, some of the material falls onto the companion and forms an accretion disk around it if the companion star is dense. Highly aligned outflows can arise from any accretion disk, even those in young stars, as the swirling material generates magnetic fields.



Magnetic fields (left, yellow lines) become twisted as a star about to form a planetary nebula rotates. Charged particles spiral along the yellow lines as they flow outward. The fields guide these particles along the star's spin axis. The white and red regions of the right panel show where the particles will flow. The white rectangular area at the center is probably the only region sufficiently dense enough for Hubble to detect. Both images: Sean Matt (University of Virginia)/Adam Frank and Eric G. Blackman (Rochester University)

If the red giant swallows its companion, the small star acts like an eggbeater as it follows a spiral descent into the star's heart. This, too, will form a disk that shapes the nebula. But the merger of two orbiting stars can also account for other puzzling shapes of the final ejection.

First, the merger provides a way of extracting and harnessing the momentum of the companion's orbit and transferring it into the dense winds from which the planetary nebula forms. Second, the merger will disrupt the red giant's core. This might explain why the largest ejection is also the final one. In particular, an entire star's worth of hydrogen fuel landing on the extremely hot core might trigger a conflagration.

Another mechanism for shaping planetary nebulae may be magnetic fields released by convection. Red giants have deep convection, but generally not deep enough to dredge material out of the core. This changes during a helium flash. The extreme heat acts like a gas flame under a pot of water. The flash causes deep material to rise quickly. If that material consists of magnetized gas, as we expect, then, as the gas surfaces, the star ejects and distorts it while it's still connected to the star's spinning surface.

But field lines stretch like rubber bands. Magnetohydrodynamic (MHD) models, which study moving magnetized fluids, reveal strange behaviors. MHD models require huge computers, clever programming methods, and shrewd guesses about the ways magnetic fields permeate the gas and exit the star's surface. The enterprise is in its infancy, and results don't always agree, so it is premature to draw vast conclusions. However, the range of outcomes explains some of the more complex nebular shapes, except for one thing: The energies and momentums of the predicted outflows are smaller than the observations require.

Looking forward

The beauty and symmetry of planetary nebulae please the eye and challenge the brain. We largely understand stellar evolution until the end. That's when we hit the limit of our understanding of the shapes and energies of mass-ejection. Stellar mergers and magnetized winds can solve some problems. New ideas will enter the discussion. For now, even with Hubble and other tools, it's too soon to tell if we're barking up the right trees.

Future instruments, especially the Atacama Large Millimeter Array (ALMA) under construction in Chile, will allow us to map the dust and possibly the magnetic fields in preplanetary nebulae. Such studies will provide essential data and propel the research for years to come. But for now, public, amateur, and professional astronomers will continue to enjoy the poetry of planetary nebulae even if we haven't figured out how stars manage to write it.