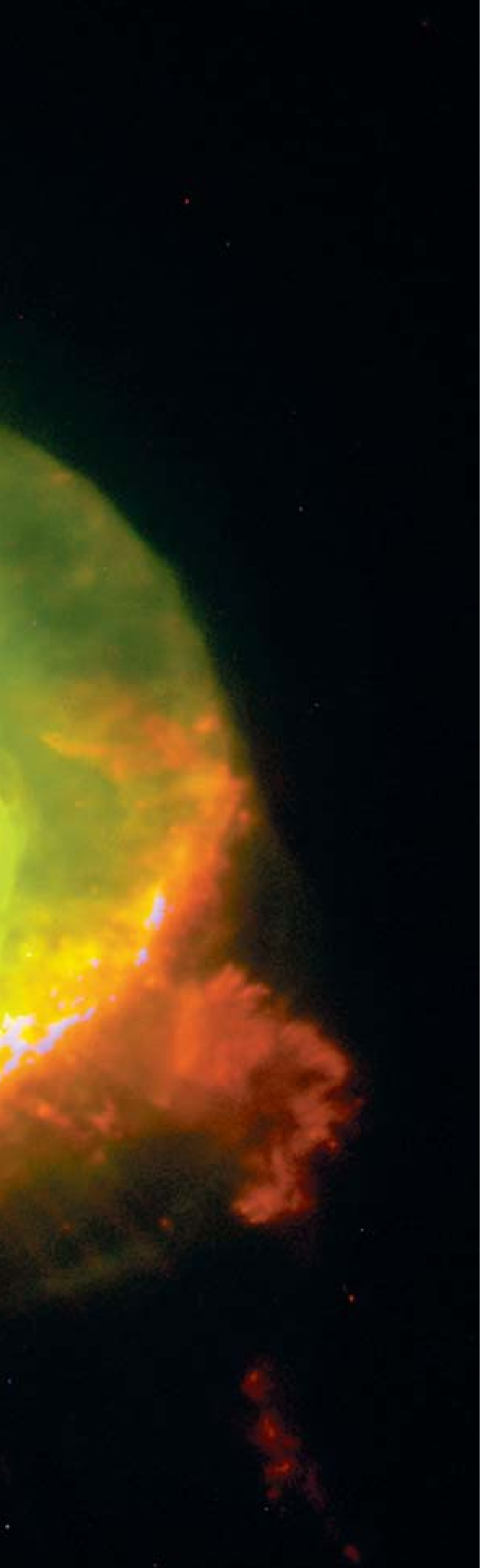
CAT'S EYE NEBULA (NGC 6543) is one of the galaxy's most bizarre planetary nebulae—a multilayered, multicolored gas cloud some 3,000 light-years from the sun. Such nebulae have nothing to do with planets; the term is a historical vestige. Instead they are the slowly unfolding death of modest-size stars. Our own sun will end its life much like this. The intricacy of the Cat's Eye, seen by the Hubble Space Telescope in 1994, sent astronomers scrambling for an explanation.



J. P. HARRINGTON *University of Maryland*, K. J. BORKOWSKI *North Carolina State University* AND NASA

THE EXTRAORDINARY

# Deaths of Ordinary Stars

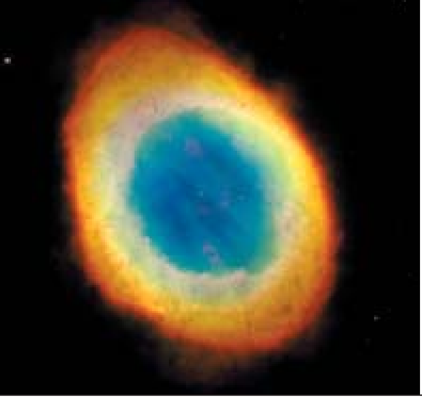
**The demise of the sun in five billion years will be a spectacular sight. Like other stars of its ilk, the sun will unfurl into nature's premier work of art: a planetary nebula**

By Bruce Balick and Adam Frank

Within easy sight of the astronomy building at the University of Washington sits the foundry of glassblower Dale Chihuly. Chihuly is famous for glass sculptures whose brilliant flowing forms conjure up active undersea creatures. When they are illuminated strongly in a dark room, the play of light dancing through the stiff glass forms commands them to life. Yellow jellyfish and red octopuses jet through cobalt waters. A forest of deep-sea kelp sways with the tides. A pair of iridescent pink scallops embrace each other like lovers.

For astronomers, Chihuly's works have another resonance: few other human creations so convincingly evoke the glories of celestial structures called planetary nebulae. Lit from the inside by depleted stars, fluorescently colored by glowing atoms and ions, and set against the cosmic blackness, these gaseous shapes seem to come alive. Researchers have given them such names as the Ant, the Starfish Twins and the Cat's Eye. Hubble Space Telescope observations of these objects are some of the most mesmerizing space images ever obtained.

Planetary nebulae were named, or rather misnamed, two cen-



RING NEBULA (M 57)

**Like all great art, planetary nebulae do more than captivate us. They cause us to question our perception of the world.**

turies ago by English astronomer William Herschel. He was a prodigious discoverer of nebulae—fuzzy, cloudlike objects visible only through a telescope. Many had a vaguely round shape that reminded Herschel of the greenish planet Uranus (which he had discovered), and he speculated they might be planetary systems taking shape around young stars. The name stuck even though the opposite turned out to be true: this type of nebula consists of gas molted from dying stars. It represents not our past but our future and our fate. In five billion years or so the sun will end its cosmic tenure in the elegant violence of a planetary nebula.

Like all great art, planetary nebulae do more than captivate us. They cause us to question our perception of the world. In particular, they pose challenges to stellar evolution theory, the physics that describes the life story of stars. This theory is a mature, supposedly well developed branch of science, one of the foundations on which all our understanding of the cosmos is based. Yet it has trouble accounting for the complex figures evident in the Hubble images. If stars are born round, live round and die round, how do they create such elaborate patterns as ants, starfish and cat's-eyes?

## Death Becomes Them

OVER THE PAST CENTURY, astronomers have come to realize that stars cleanly separate into two distinct classes as they die. The elite massive stars—those with a birth weight exceeding eight solar masses—explode suddenly as supernovae. More modest stars, such as the sun, have a drawn-out death. Instead of detonating, they spend their last years burning their fuel spasmodically, like an automobile engine running out of gas.

Nuclear reactions in such a star's core, the source of power for nearly its entire life, deplete the available hydrogen, then the helium. As the nuclear burning moves outward to the fresh material in a shell surrounding the core, the star bloats into a so-called red giant. When the hydrogen in the shell, too, is exhausted, the star takes to fusing helium there. In the process, it becomes unstable. Deep convulsions, combined with the pressure of radiation and other forces, heave the distended and loosely bound surface layers outward into space, creating a planetary nebula.

## Overview/*Planetary Nebulae*

- Adorning the entire Milky Way like so many Christmas tree ornaments, planetary nebulae are the colorful remnants of modest stars—those less than eight solar masses. As these stars sputter toward death, they molt their outer layers in the form of a "wind" that blows outward at up to 1,000 kilometers per second. The stars gradually strip down to their deeper, hotter layers, the ultraviolet light from which ionizes the wind and causes it to fluoresce.
- Hubble Space Telescope images have revealed nebulae with surprisingly complex shapes, which are still only vaguely understood. Magnetic fields trapped in the core and released into the wind may play a role. So may close companion stars or large planets, whose tidal forces shepherd gas into giant rings that, in turn, funnel the wind into an hourglasslike shape.

Since the 18th century, astronomers have imaged and catalogued about 1,500 planetary nebulae, and another 10,000 may lurk out there, hidden behind dense clouds of dust in our galaxy. Whereas a supernova goes off in the Milky Way every few centuries, a new planetary nebula forms every year, as hundreds of older ones fade into obscurity. Supernovae may be flashier, but their debris is roiling and chaotic, lacking the symmetry and intricacy of these nebulae.

Planetary nebulae are not as airy and tranquil as their images suggest. Au contraire, they are massive and tempestuous. Each contains the equivalent of about a third the mass of the sun, including nearly all of the star's remaining unburned nuclear fuel. Initially the loosely bound outer layers stream off the star at 10 to 20 kilometers per second—a relatively slow outflowing wind that will carry the bulk of the nebula's eventual mass. As the star strips down to its still hot core, it evolves from orange to yellow, then white, and finally blue. When its surface temperature exceeds about 25,000 kelvins, it bathes the surrounding gas in harsh ultraviolet light, which has enough punch to dismember molecules and strip atoms of their electrons.

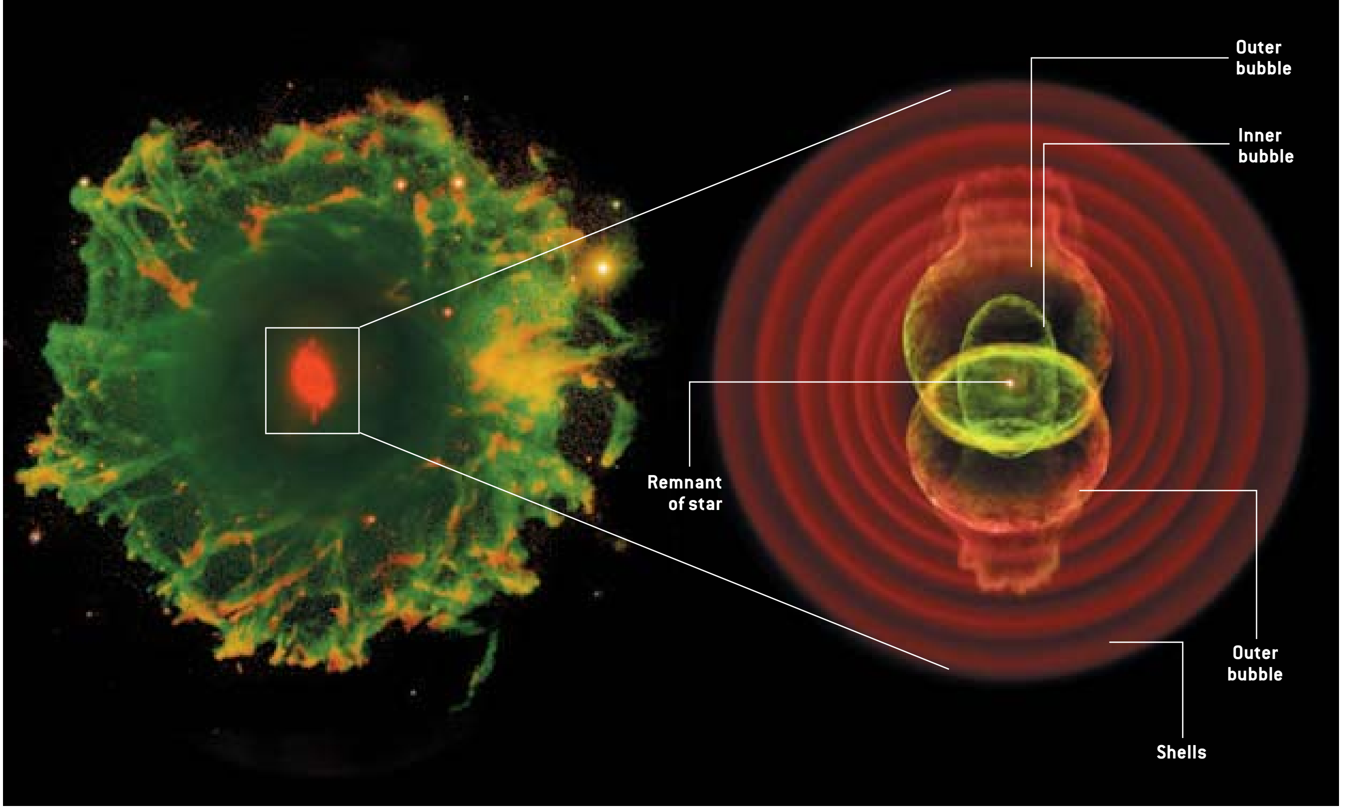
The stellar wind carries ever less mass at ever increasing speed. After 100,000 to one million years, depending on the original mass of the star, it ceases altogether, and the remnant star settles down as an extremely dense and hot white dwarf—a stellar ember crushed by gravity into a nearly crystalline orb about the size of Earth.

Because the forces that are supposed to drive off mass from dying stars are spherically symmetrical, astronomers before the 1980s thought of planetary nebulae as expanding spherical bubbles [see

NASA/ESA AND J. HESTER *Arizona State University*; NASA AND HUBBLE HERITAGE TEAM (STScI/AURA)

# THE CAT'S EYE DISSECTED

The image on the preceding pages shows just part of the full glory that is the Cat's Eye. A ground-based telescope image (*left*) reveals the "eyelashes"—a ragged outer band of gas. The inner region, or "pupil," which an artist has reconstructed here (*right*), consists of a remnant star encased in an egg-shaped layer of gas, which in turn is surrounded by two off-center bubbles, which in turn are surrounded by concentric gas shells. Evidently the star ejected material in distinct stages over the course of millennia. The upper part of the nebula is tilted toward the viewer.




R. CORRADI *Institute of Astrophysics of the Canary Islands* (*left*); DON DIXON (*right*)

"Planetary Nebulae," by Martha and William Liller; Scientific American, April 1963]. Since then, the picture has steadily gotten far more complicated—and far more interesting.

## Whistling in the Dark

THE FIRST SIGN THAT planetary nebulae are more than just stellar burps came in 1978, when ultraviolet observations showed that dying stars continue to blow winds long after they eject their outer gaseous layers. Though tenuous, these later winds top out at about 1,000 kilometers per second, 100 times as fast as the denser winds that preceded them.

To account for their effects, Sun Kwok of the University of Calgary, Christopher R. Purton of the Dominion Radio Astrophysical Observatory in Canada and M. Pim Fitzgerald of the University of Waterloo borrowed a stellar winds model that had been developed for other astrophysical phenomena. The idea is that when the fast winds ram into the slower ones upstream, a dense rim of compressed gas forms at the interface, much like the rim of snow at the front of a plow. The rim of gas surrounds a nearly empty (but very hot) cavity, and over time the fast wind clears out an ever larger volume.

This model, now called the interacting stellar winds hypothesis, works well for round or nearly round planetary nebulae. Observers in the 1980s, however, began to realize that round nebulae are the exception, perhaps just 10 percent of the total population. Many of the others have a prolate, or egglike, shape. The most spectacular, though rare, nebulae comprise two bubbles on opposite sides of the dying star. Astronomers call them "bipolar." "Butterfly" or "hourglass" would be a more vivid description.

To explain these shapes, the two of us, along with Vincent Icke and Garrelt Mellema, then both at Leiden University in the Netherlands, extended the interacting winds concept. Suppose that the slow winds first manage to form a dense torus orbiting the equator of the star. Later, this torus gently deflects the outflowing stellar winds in a polar direction. An elliptical nebula results. Hourglasslike nebulae are those with a very tight, very dense torus. The torus serves as a nozzle, as your lips do when you whistle, collimating your exhaled breath into a narrow jet of air. Similarly, the torus strongly deflects the fast winds, producing a mirror-image pair of jets or hourglass-shaped streams of gas.

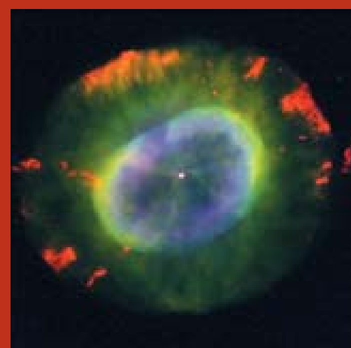
The model was simple, and it nicely fit

# The Art of Planetary Nebulae

Hubble Space Telescope images have revealed planetary nebulae to be far more intricate and diverse than theorists ever expected.

The Stingray nebula (Hen 3-1357), the youngest known planetary, started to glow just 20 years ago. A companion star and a torus of gas may account for its shape.

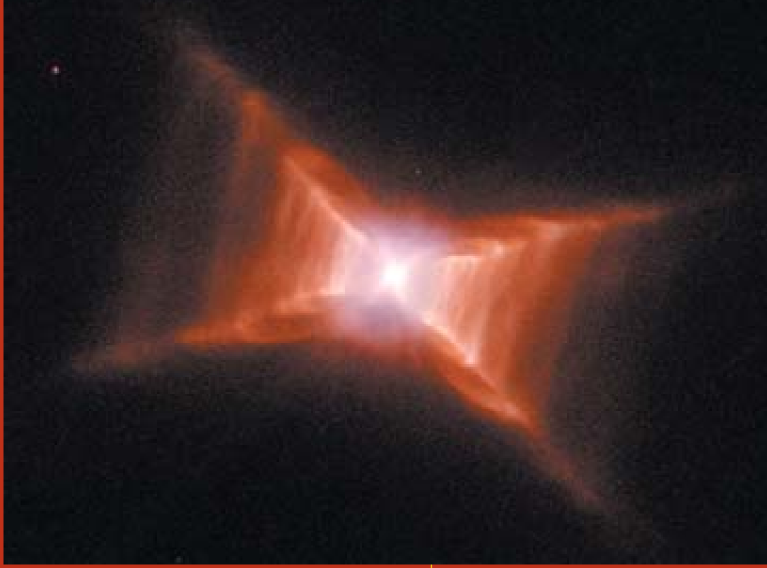
Encased in a dense, dusty, carbon-rich torus (*upper right*), the central star of the Bug nebula (NGC 6302) is one of the hottest known.



The Blue Snowball nebula (NGC 7662) contains so-called FLIERS (*red splotches*), fast-moving knots of gas of uncertain origin.

At the center of the Twin Jet nebula (M 2-9) are a binary star system and a gaseous disk 10 times the diameter of Pluto's orbit. Blue shows hydrogen ions; red, oxygen atoms; and green, nitrogen ions.

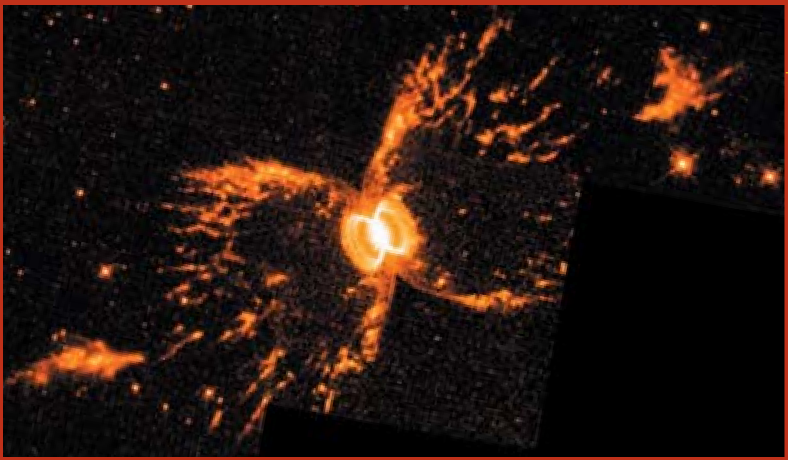
Gas streams out from the central star of the Ant nebula (Menzel 3) at 1,000 kilometers per second.



The Red Rectangle nebula (HD 44179) has a boxy shape because we are seeing nested cones of gas from the side. For an interactive image, visit www.spacetelescope.org/images/html/zoomable/heic0408a.html

Like a searchlight, the central star of the Egg nebula (CRL 2688) illuminates concentric shells of dust, which extend over a tenth of a light-year from the star. The colors represent light polarized in different directions.

The Dandelion Puff Ball nebula (NGC 6751) is an example of an elliptical planetary nebula. Red, green and blue correspond to weakly, moderately and strongly ionized gas, respectively.



This image of the Southern Crab nebula (He2-104), which captures the glow of nitrogen gas, reveals a small, bright nebula embedded in a larger one. The red giant that created the nebula is orbited by a white dwarf star.

ESA/NASA AND A. ZIJLSTRA *University of Manchester* (*Bug*); M. BOBROWSKY *Orbital Sciences Corp.* AND NASA (*Stingray*); B. BALICK AND J. ALEXANDER *University of Washington*, A.HAJIAN *U.S. Naval Observatory*, Y. TERZIAN *Cornell University*, M. PERINOTTO *University of Florence*, P. PATRIARCHI *Arcetri Observatory* AND NASA (*Blue Snowball*); B. BALICK, V. ICKE *Leiden University*, G. MELLEMA *Stockholm University* AND NASA (*Twin Jet*); NASA/ESA AND HUBBLE HERITAGE TEAM (STScI/AURA) (*Ant*); NASA/ESA, H. VAN WINCKEL *Catholic University of Leuven* AND M. COHEN *University of California, Berkeley* (*Red Rectangle*); NASA AND HUBBLE HERITAGE TEAM (STScI/AURA) (*Egg*); NASA AND HUBBLE HERITAGE TEAM (STScI/AURA) (*Dandelion Puff Ball*); R. CORRADI *Institute of Astrophysics of the Canary Islands*, M. LIVIO *STScI*, B. BALICK, U. MUNARI *Astronomical Observatory of Padua/Asiago*, H. SCHWARZ *Nordic Optical Telescope* AND NASA (*Southern Crab*)

## Terra-Cotta

Planetary nebulae are a glimpse into the future of our own solar system. When the sun reaches the eleventh hour of its life, it will swell to the size of Earth's present orbit, causing Mercury and Venus to burn up like giant meteors. Earth will escape this fate because the sun will have blown out some of its material, weakening its gravity so that our planet slips into a new, larger orbit. The ochre-red sun will fill the noon sky. As one edge sets in the west, the other will begin to rise in the east. Though cooler than today (2,000 kelvins rather than 5,800 kelvins), it will still bake the planet's surface to a nice hard finish.

In these reduced circumstances, Earth will witness the formation of a planetary nebula from the inside. The sun will eject its outer layers in an extreme version of the present-day solar wind. Eventually the red behemoth will be stripped to its core, which will quickly settle down as a white dwarf star. Lit by this blue-hot pinprick, objects on Earth will cast sharp-edged, pitch-black shadows; sunrise and sunset will take no longer than an eyeblink. Exposed rock will turn to plasma as ultraviolet radiation from the dwarf destroys all molecular bonds, coating the surface with an eerie iridescent fog, constantly lifting and swirling. As the dwarf radiates away its energy, it will fade into a cold, dark cinder. Thus, our world will end first in fire, then in ice. *—B.B. and A.F.*

TOASTED BY THE RED GIANT SUN, the future Earth will at least be a good spot to watch the unfolding of a planetary nebula.

RON MILLER

all the images available by 1993. Supercomputer simulations confirmed the viability of the basic idea, and new observations verified that the slow wind really did appear denser near the equator. We did not attempt to explain why the slow wind would be ejected as a torus, hoping that particular detail would be filled in later.

Our confidence in the model was quickly deflated. In 1994 Hubble took its first clear image of a planetary nebula, the Cat's Eye (designated NGC 6543), first seen by Herschel. That fateful picture blew us off our chairs. One of its two crossed ellipses, a thin rim surrounding an ellipsoidal cavity, matched the model. But what were all those other structures? No one had predicted that clumpy red-colored regions would lace the nebula; jetlike streaks immediately outside it were stranger still. At best, the interacting winds model could be just partly correct.

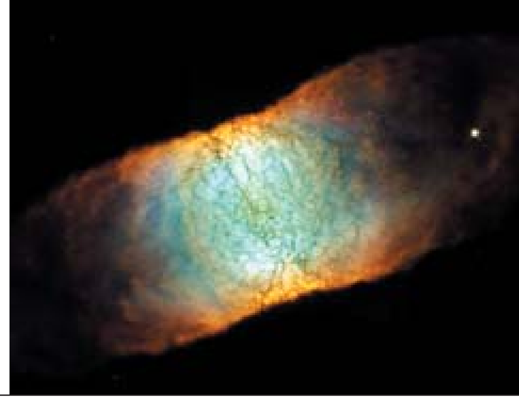
### Sweating the Theoreticians

A POPULAR SCIENTIFIC IDEA is not easy to overturn, even when faced with images like those from Hubble. We went into professional denial, hoping the Cat's Eye was an anomaly. It was not. Other Hubble images soon established beyond doubt that some fundamental piece was missing from our picture of how stars die. Egos aside, this was the best place for scientists to find themselves. When cherished ideas are in ruins at your feet, nature is challenging you to look at the world anew: What have you missed? What have you not thought of before?

In such situations, it helps to focus on the most extreme cases, because they are where the unknown shaping forces may be operating most distinctly. Among planetary nebulae, the most extreme cases are the bipolar objects. The Hubble images of these objects look as if they had been taken from Georgia O'Keeffe's exquisite flower series. The small-scale features that dapple the nebulae come in mirror-image pairs, one on each side of the nebula. This reflection symmetry implies that the entire structure was assembled coherently by organized processes operating near the stellar surface, something like the making of a snowflake or sunflower.

For these objects, the interacting winds model makes a readily testable prediction: once gas leaves the torus, it

**Planetary nebulae are not as airy and tranquil as their images suggest. They are massive and tempestuous.**



RETINA NEBULA (IC 4406)

NASA AND HUBBLE HERITAGE TEAM (STScI/AURA)

flows outward at a steady speed, which in turn produces a distinctive Doppler shift in the light emitted by the gas. Unfortunately, the model fails this test. In 1999 one of us (Balick) and Romano Corradi (now at the Institute of Astrophysics of the Canary Islands) and their collaborators used Hubble to study the Southern Crab nebula (designated He2-104). They found that its expansion velocity increased in proportion with distance from the star. The gas farthest away got there simply because it was moving the fastest. Extrapolating back in time, the lovely hourglasslike nebula seemed to have formed in a single eruption from the star about 5,700 years ago. That made the interacting winds model, which presumes that a continuous wind shapes the nebula, irrelevant.

Even stranger, Corradi and his colleagues found that the Southern Crab nebula was really two nebulae, one nested inside the other like Russian *matryoshka* dolls. We had guessed that the inner nebula was simply the younger of the two, but observations clearly showed that both nebulae had exactly the same pattern of increasing speed with distance. Thus, all of the complex structure must have formed during just one lavishly choreographed event six millennia ago. To this day, we puzzle over these findings.

The coffin lid of the interacting winds model was hammered shut in the late 1990s, when Kwok, Raghvendra Sahai and John Trauger of the Jet Propulsion Laboratory in Pasadena, Calif., Margaret Meixner of the University of Illinois and their co-workers published a new class of Hubble images. Their targets were very young planetary nebulae, caught before or shortly after the star ionized and heated them. Astronomers had expected that these objects would be smaller but otherwise similar versions of the more mature variety. Once again we were wrong: Embryonic and juvenile planetary nebulae have far more playful shapes. Their multiple axes of symmetry simply cannot be explained by the nozzle we had hypothesized. As Sahai and Trauger intimated in their 1998 paper on these objects, the time had come to find a different paradigm.

## Stirring the Pot

THE OUTLINES OF fruitful theories for the shaping of planetary nebulae continue to emerge. The trick is to develop models that embrace the entire vexing array of observations. Researchers now agree that one of the principal players is the gravitational influence of companion stars. At least 50 percent of all the "stars" you see at night are really pairs of stars orbiting each other. In most of these systems, the stars are so far apart that they develop independently. But in a small fraction, the gravity of one star can deflect or even control the material flowing out of another. This fraction matches the fraction of planetary nebulae that are bipolar.

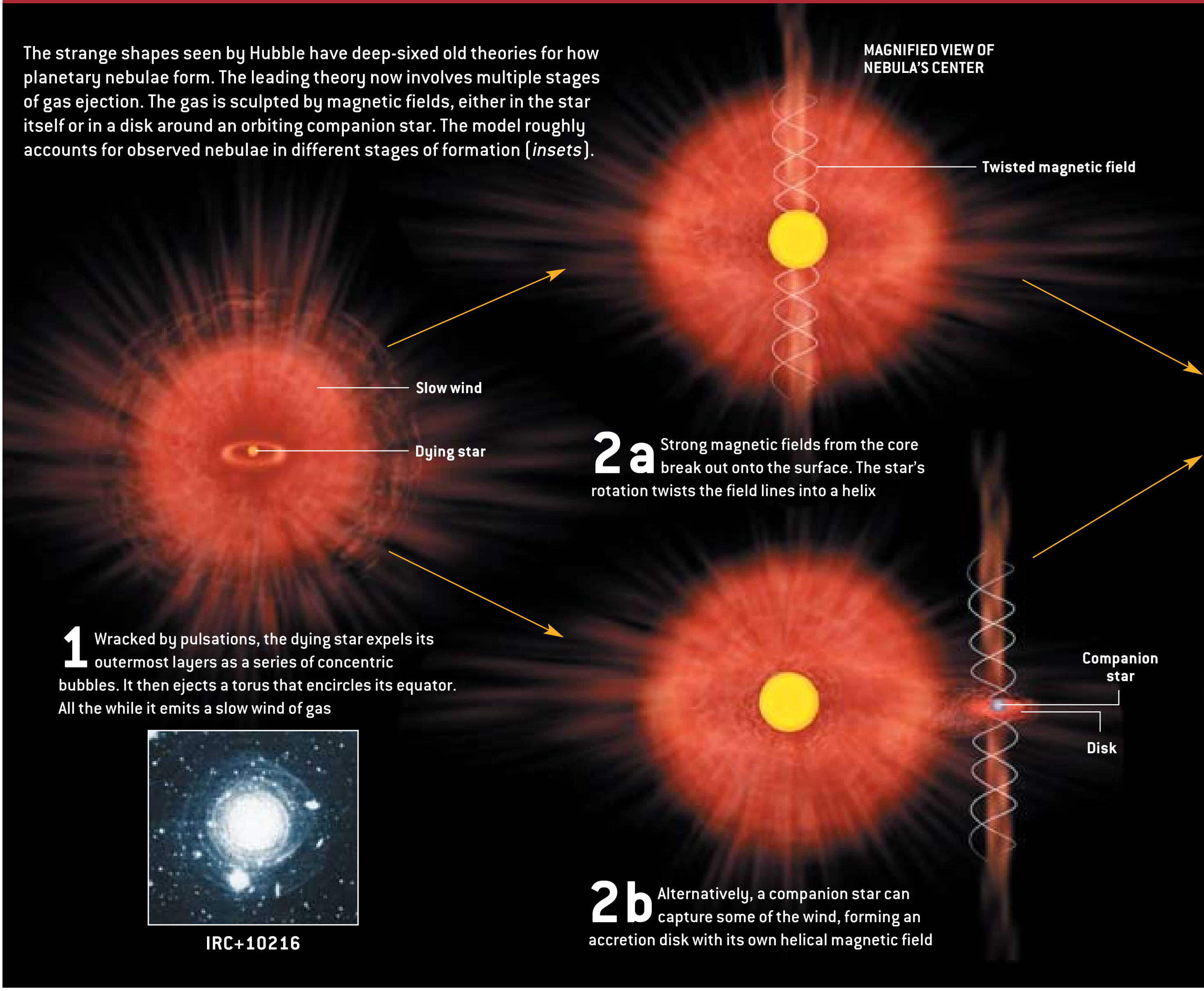
Mario Livio of the Space Telescope Science Institute and his former student Noam Soker of the Technion-Israel Institute of Technology championed this idea many years before it became fashionable [see "Planetary Nebulae," by Noam Soker; SCIENTIFIC AMERICAN, May 1992]. According to their scenario, the companion captures the material flowing from the dying star. In a system where the orbits are smaller than Mercury's and an orbital "year" is measured in Earth days, this transfer is cumbersome. By the time that material from the dying star reaches the companion, the latter has scooted well ahead in its orbit. The material drawn tidally from the large dying star thus forms a tail that chases the denser companion star from behind. This tail eventually settles into a dense, thick disk that swirls around the companion. Later simulations show that even a companion with an orbit as wide as Neptune's could scoop up an accretion disk.

The saga can take an interesting twist. As the dying star swells in size, it can swallow up its companion and disk. The result is a case of cosmic indigestion. The companion and disk enter a spiral orbit inside the body of the larger star, reshaping and flattening it from within. The outflows can thrash about, forming curved jets. Gradually the companion sinks deeper into the star until it merges with the core, at which point the outflow is cut off. This process could explain why some nebulae appear to result from an outflow that came to an abrupt end.

**THE AUTHORS**

*BRUCE BALICK* and *ADAM FRANK* have published dozen of papers, both observational and theoretical, on planetary nebulae and their precursor stars. Balick remembers deciding to become an astronomer at age five when his father read him a book about the planets. He has worked in fields ranging from star formation to active galactic nuclei and is now chair of the astronomy department at the University of Washington. Frank fell in love with astronomy around the same age, inspired by the covers of the science-fiction magazine *Amazing Stories* in his father's library. Growing up in the New York area, he soon discovered he could see only four or five stars in the night sky, so his attention turned to theory. Now a professor at the University of Rochester, Frank is interested in many topics in astrophysical fluid dynamics, from the death of stars to the birth of planets.

# AS A STAR DIES, A NEBULA IS BORN



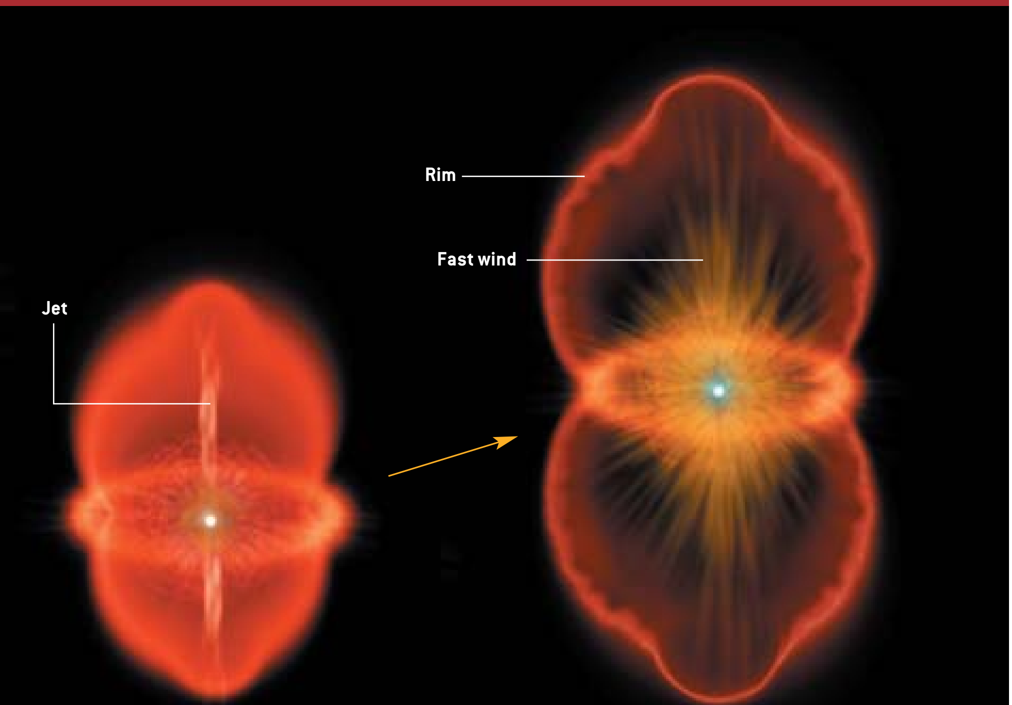

## Magnetic Guidance

COMPANION STARS in binary systems are not the only plausible sculptors of planetary nebulae. Another player may be powerful magnetic fields embedded in either the star or the disk that forms around its companion. Because much of the gas in space is ionized, magnetic fields can guide its motion. Strong fields act like stiff rubber bands that shape the gas flow, much as Earth's magnetic field snares particles from the solar wind and guides them into the polar regions to trigger auroras. Conversely, strong winds can stretch, bend or entangle the fields.

In the mid-1990s Roger A. Chevalier and Ding Luo of the University of Virginia proposed that outflowing stellar winds carry hoops of magnetic field. The tug of war between the gas and the field can collimate the outflow into exotic shapes. Unfortunately for the model, it predicts that the field must begin in a weak state and play no role in generating the wind. That is a problem, because active magnetic fields on the surfaces of stars do seem to be instrumental in launching winds.

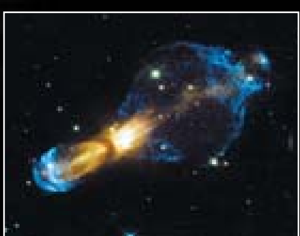
Another route has been to explore how strong magnetic fields can fling matter into space. As convection roils a dying star, fields anchored to the core rise with buoyant gas to the surface and, if the core is rotating rapidly, get wound up like a spring. As they break out at the surface, they snap and shoot material outward. A similar process can occur in a magnetized accretion disk. In fact, the star and accretion disk can each power a set of winds. A misalignment of their axes might produce some of the strange multipolar shapes seen in young planetary nebulae. Along with Eric G. Blackman of the University

DON DIXON (*illustrations*); COURTESY OF N. MAURON AND P. J. HUGGINS IN *ASTRONOMY AND ASTROPHYSICS*, VOL. 359; 2000 (*IRC+10216*)




**3** Whatever its origin and location, the magnetic field funnels gas into a short-lived jet, which plows into the slow-moving wind. Meanwhile the torus causes the wind to take on an hourglass shape

**4** The star emits a fast-moving wind, which hits the slow-moving wind from behind and builds up a rim of gas



**CALABASH (OH 231.8+4.2)**

**HUBBLE'S DOUBLE BUBBLE**

NASA/ESA AND V. BUJARRABAL *National Astronomical Observatory of Spain* (*Calabash*); B. BALICK, V. ICKE, G. MELLEMA AND WFPC2/HST/NASA (*Double Bubble*)

of Rochester, Sean Matt of McMaster University and their colleagues, one of us (Frank) is studying these effects. The key is that magnetic fields, like binary stars, provide extra forces that can generate a far greater range of shapes than the interacting winds model can.

Our understanding of how dismembered stars are sculpted into planetary nebulae has made some progress but is still immature. The overall description of stellar death is well accepted. Stars evolve in such a way that their engines sputter as they shut down and shed their outer layers into space. In fact, the theory of stellar structure and evolution is one of the most successful scientific theories of the 20th century. It exquisitely explains observations of most stars—their light output, their colors, even most of their quirks. But large gaps clearly remain, especially at the very beginning and very end of stars' lives.

Not far from the University of Rochester is the Eastman School of Music. There some of the world's best young musicians and composers struggle every day to develop ways to express their creative visions. Those of us who study the death of sunlike stars find ourselves in a similar position. We believe that we have identified the instruments of how dying stars shape their outflows. What we do not yet understand is how these laws are orchestrated to create something as harmoniously structured as a planetary nebula. What powers the stellar winds? When are companion stars important? What role do magnetic fields play? What creates multiple-lobed nebulae?

We are hardly the only astrophysicists to be awed, puzzled and challenged by enigmatic images from Hubble and other instruments over the past decade. Nearly every field of astronomical research has a similar tale to tell. New information ultimately upends the best of theories in every field of research. That is the nature of progress. Discovery is often disruptive. It clears out old niches and prepares the way for big (and often disorienting) leaps forward. Scientific theories are built to be used, but they must be mistrusted, tested and improved. SA

## MORE TO EXPLORE

**The Shapes of Planetary Nebulae.** Bruce Balick in *American Scientist,* Vol. 84, No. 4, pages 342–351; July 1996.

**Cosmic Butterflies: The Colorful Mysteries of Planetary Nebulae.** Sun Kwok. Cambridge University Press, 2001.

**Shapes and Shaping of Planetary Nebulae.** Bruce Balick and Adam Frank in *Annual Review of Astronomy and Astrophysics,* Vol. 40, pages 439–486; 2002.

A variety of Web sites have images of planetary nebulae:

**www.astro.washington.edu/balick/WFPC2**
**www.blackskies.com/intro.html#NEBULAE**
**hubblesite.org/newscenter/archive/category/nebula/planetary**
**ad.usno.navy.mil/pne**

For more on stellar evolution, see:
**www.astronomynotes.com/evolutn/s1.htm**
**www.blackskies.com/neb101.htm**
**observe.arc.nasa.gov/nasa/space/stellardeath/stellardeath_intro.html**