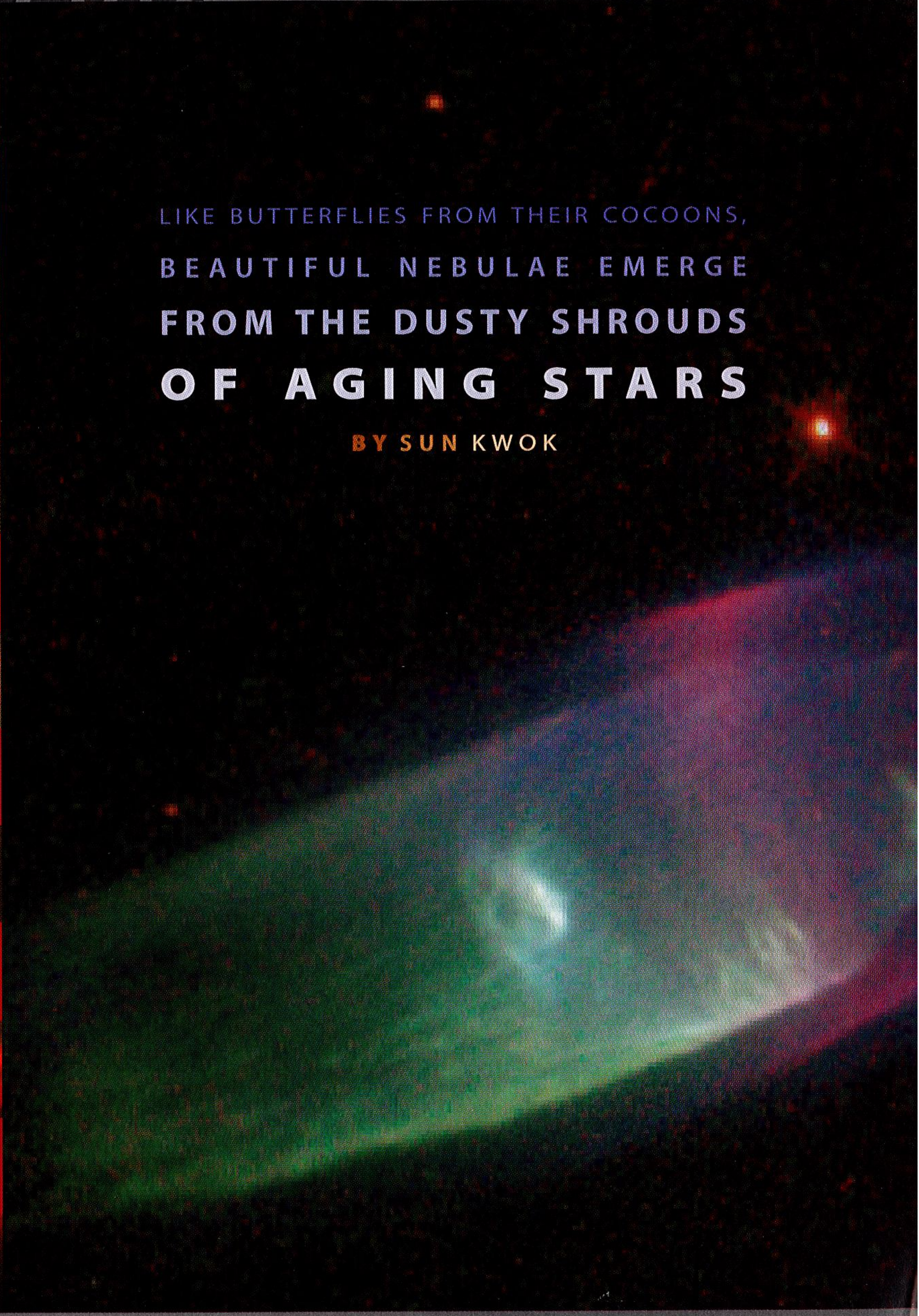
STELLAR METAMORPHOSIS

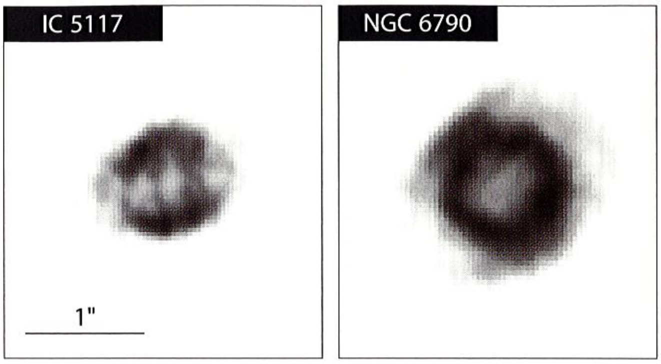
LIKE BUTTERFLIES FROM THEIR COCOONS, BEAUTIFUL NEBULAE EMERGE FROM THE DUSTY SHROUDS OF AGING STARS

BY SUN KWOK



As the saying goes, nothing lasts forever. Not even stars. The Sun, for example, was born approximately four and a half billion years ago and is expected to last another five billion years. While it is a popular myth that stars explode when they die, this is true only for the most massive of them. More than 95 percent, including the Sun, will go quietly — not with a bang but a whimper.

Ophiuchus is home to M2-9, also known as the Butterfly Nebula, a bipolar planetary nebula imaged by Hubble. The visible-light radiation from this object is a combination of reflected starlight and finely tuned "line" emission, implying that the Butterfly is in between the proto-planetary and planetary-nebula stages. In this WFPC2 image, line emissions from neutral oxygen are colored red, ionized nitrogen green, and doubly ionized oxygen blue.



The actual nebulosity around a young planetary can be very small and quite difficult to image at visible wavelengths. With the interferometric capabilities of modern radio telescopes, however, these objects can be resolved when they are as small as one arcsecond across. These images were taken with the Very Large Array in Socorro, New Mexico, and are courtesy the author.

During the last ten thousand years of life, stars with masses up to eight times that of the Sun go through a glorious stage in which they produce planetary nebulae — magnificent displays of color and light. Not only bright in visible light, planetary nebulae are also radio, infrared, and even X-ray sources. They can be considered a Sun-like star's last hurrah. But to better understand how stars die, we have to look a few hundred years before a planetary nebula makes its appearance. The obvious name for this progenitor phase is the *proto-planetary nebula,* and this type of nebula has come into its own as a fascinating subject of research.

A full-grown planetary nebula is completely ionized by the ultraviolet light from its central hot star. A proto-planetary nebula's central star, on the other hand, is relatively cool and does not emit ultraviolet light, so the nebula itself is made of neutral (un-ionized) material. It shines by reflected light only, like our Moon and planets. In this article you can follow an evolutionary sequence, from the Egg Nebula (a proto-planetary) below to the Butterfly Nebula (an extremely young planetary) on page 31 and finally to Hubble 5 (a true planetary nebula) on the facing page. All share a common bipolar shape.

The First of Its Kind

In the 1970s astronomers at the University of Minnesota found that many red-giant stars lose mass very rapidly, at a rate of up to one hundred-thousandth, or 10^{-5}, solar mass per year. (In comparison, the Sun releases only a one-hundred-*trillionth,* or 10^{-14}, of its mass per year in its wind.) For some red giants the amount of gas and dust ejected is so great that the stars are completely obscured from view and can be identified only by the infrared radiation emitted by the circumstellar dust. It soon became clear that many of the most evolved stars can be found only by searching for emissions at midinfrared wavelengths.

The first survey of the midinfrared sky was made by the Air Force Geophysical Laboratory (AFGL). Nine rockets were launched between 1971 and 1974, with each carrying a cryogenically cooled 16.5-centimeter telescope. The AFGL surveyed 90 percent of the sky at a wavelength of 11 microns and cataloged more than 2,000 sources. The task of identifying these objects fell to Ed Ney, then of the University of Minnesota, and Michael Merrill, then of the University of California at San Diego. Among the targets they pinpointed in this ground-based observing program was number 2688 in the AFGL catalog. It was found to be associated with a nebulous object. Merrill named it the Egg Nebula, based on its appearance on Palomar Observatory Sky Survey plates. With hindsight this is somewhat of a misnomer because higher-resolution pictures have since shown that the Egg has two separate lobes.

At the time of its discovery, no one was sure whether the Egg was young or old. David Crampton (Dominion Astrophysical Observatory) and Anne Cowley (University of Michigan) took a visible-light spectrum with the Dominion Astrophysical Observatory's 1.8-meter telescope. They classified the Egg as a star of spectral type *F*5 Ia. According to conventional wisdom, this made it a supergiant with greater than 10 times the mass of the Sun. However, certain molecular absorption features did not fit this interpretation. As we found out later, these spectral characteristics would help us identify other proto-planetary nebulae. History had unknowingly been made: the first proto-planetary nebula had been discovered.

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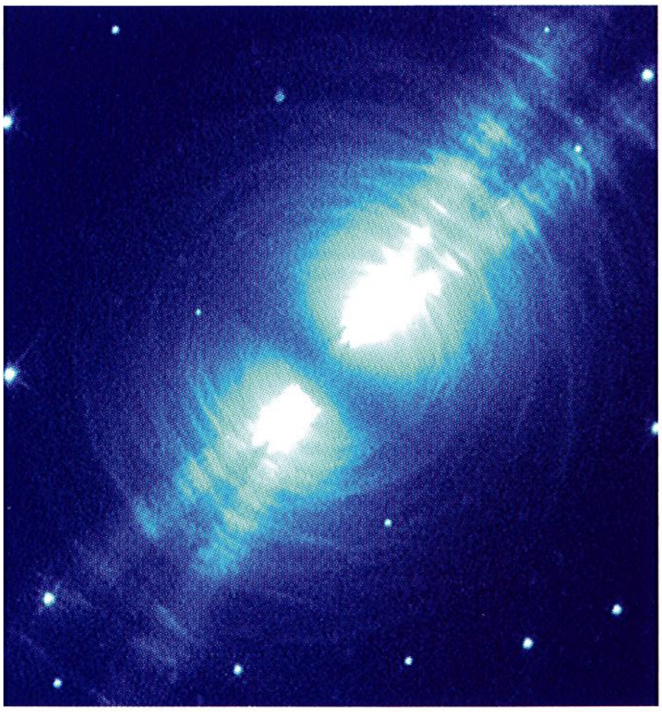


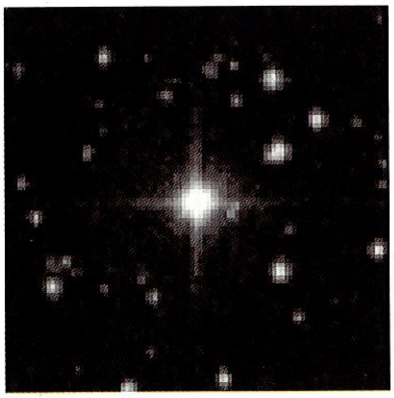
In this image of the Egg Nebula — the first proto-planetary nebula discovered — two beams define the edges of light cones emerging from the dying star's poles. The dark lane dividing the nebula is a dust torus that obscures the star. Hubble Space Telescope Wide Field and Planetary Camera 2 image courtesy Raghvendra Sahai and STScI.

Even though Hubble 5 in Sagittarius is a planetary nebula that has entered adulthood, its morphology still reflects its youth.

The IRAS Era

If stars are wrapping themselves deeper in dust shells as they evolve into red giants, then many of the most evolved stars probably escaped detection. And since planetary nebulae follow the red-giant phase, then proto-planetary nebulae must also be infrared sources and a deeper probe than the AFGL survey might uncover them as well. The Infrared Astronomy Satellite promised to do just that.

In January 1982, during a workshop on stellar evolution held at the Kitt Peak National Observatory, Merrill burst into the meeting room to announce that IRAS had been successfully launched. I was giving a talk at the workshop on the formation of planetary nebulae and the predicted properties of proto-planetary nebulae, and thus I was particularly excited. In the 10 months before it ran out of coolant, IRAS surveyed 97 percent of the sky and cataloged more than 250,000 sources.



The bright "star" in the middle of this image is IRAS 18095+2704, a proto-planetary nebula in Hercules. Based on this visible-light image alone we would never know that it is such an interesting object. Only by their spectra can proto-planetaries be properly identified.

The mission was a tremendous success.

From their size and expansion velocities, astronomers knew that planetary nebulae had lifetimes of about 10,000 years. Using preliminary data from IRAS, Stuart Pottasch (University of Gröningen) estimated that the satellite had detected as many as 1,000 planetaries. Furthermore, stellar evolution theories developed by Bohdan Paczynski (then of the Copernicus Astronomical Center) and Detlef Schönberner (then of the University of Kiel) predicted that proto-planetary nebulae should live about one-tenth as long as planetary nebulae. Taken together, these ideas suggested there should be about 100 proto-planetary nebulae in the IRAS catalog.

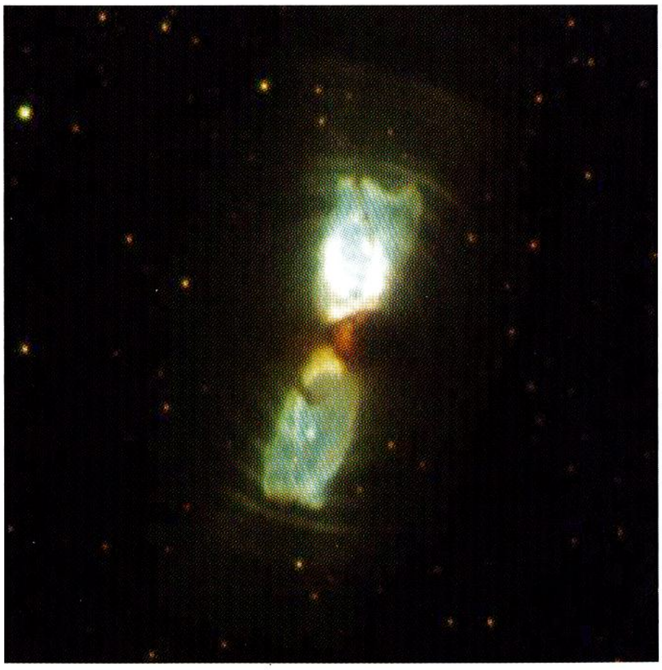
The classification of planetary nebulae as such is based not on their appearance but on the strong emission lines in their spectra. Often they appear starlike, with no observable structure, because of their small angular sizes. Ground-based optical telescopes are limited by the Earth's atmosphere to an angular resolution of about one arcsecond. Since 1980 the Very Large Array (VLA) in New Mexico has allowed radio sources to be imaged with 10 times better angular resolution. In 1983 I embarked on a project to resolve many of these "stellar" planetary nebulae by using the VLA.

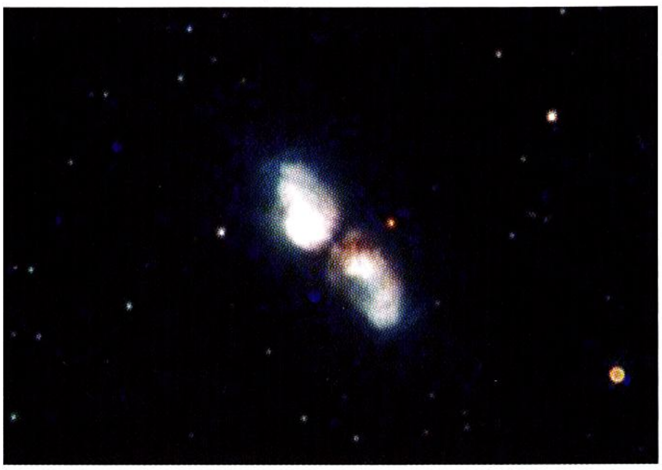
Because planetary nebulae expand with time, their radio surface brightnesses are expected to decrease as the nebulae age and become more diffuse. The youngest planetaries are therefore small and radio bright. Over a period of several years, my graduate student Orla Aaquist and I analyzed hundreds of planetary-nebula images obtained with the VLA, and we were able to identify a group of very young specimens.

ASTRONOMERS HAVE LONG BEEN PUZZLED BY THE MORPHOLOGICAL VARIETY AND RICHNESS OF PLANETARY NEBULAE

Armed with this sample of young planetaries, we compared its IRAS-measured colors with those of evolved red giants. To our amazement we found a gap in the colors between these two groups. Since red giants are expected to evolve into planetary nebulae, objects that occupy this gap must be objects in the transition phase, or proto-planetary nebulae.

By searching through the IRAS catalog for objects with colors that fit into this gap, Kevin Volk (University of Calgary), Bruce Hrivnak (Valparaiso University), and I selected a list of candidates and searched for their visual counterparts with the Canada-France-Hawaii Telescope (CFHT), the United Kingdom Infrared Telescope, and the 4-meter telescope at the Cerro Tololo Inter-American Observatory. In the plane of the Milky Way, where the density of stars is very high, there can be dozens or even hundreds of stars near the positions of IRAS sources. The only foolproof way to identify them was to search around the IRAS position using a midinfrared detector. In doing so, we found many very evolved stars and a few very young ones (which also often have dust shells). But we detected no clear signs of proto-planetary nebulae.





Then on May 26, 1996, Hrivnak and I were observing at the CFHT when we turned the telescope to IRAS 18095+2704, an infrared source in Hercules. Since most of the IRAS sources have faint visible-light counterparts, we turned up the gain on the monitor. When we scanned the position, a bright star zapped into view, almost burning out the screen! This IRAS source was a 10th-magnitude star — bright, but not bright enough to be included in any existing star catalog. Subsequent spectroscopic observations by Hrivnak identified it as spectral type *F*3 Ib, definitely not an evolved red giant or a young star but a luminous star of intermediate temperature.

We determined IRAS 18095+2704 had just emerged from its dust cocoon, and was therefore almost certainly a proto-planetary nebula. As the star stopped losing mass at the end of the red-giant phase, we reasoned, its dust shell gradually dispersed with time. Eventually the star's light could be seen through the shell. From model calculations, we estimated that IRAS 18095+2704 left the red-giant branch of stellar evolution about 300 years ago.

Many similar discoveries soon followed. We have since found more than a dozen other yellow (spectral classes *F* or *G*) supergiants with molecular absorption lines, just like the Egg Nebula's. These objects all belong to a very-high-luminosity class by comparison with spectral standards. However, this doesn't mean they are massive supergiant stars, as a strict interpretation of the "rules" would imply. In fact, they are only a few thousand times brighter than the Sun, rather than 30,000 or 40,000 times brighter as true supergiants are. When the "rules" were formulated by William Morgan and Philip Keenan in 1943, these strange stars were unknown! And far from being massive objects, proto-planetaries have only a fraction of the Sun's mass. When they were on the main sequence these stars may have had several times the mass of the Sun, but most of it was shed in the preceding red-giant phase.

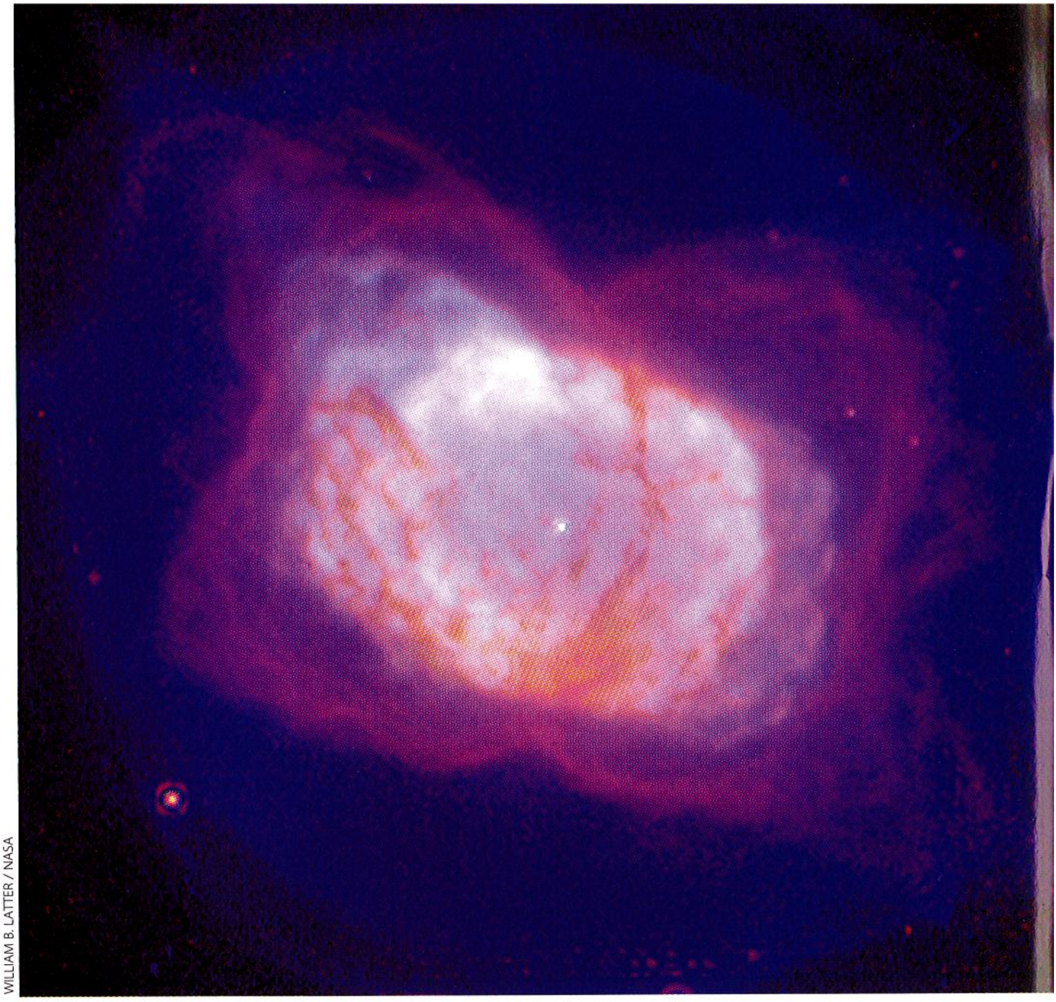
While proto-planetary nebulae have very similar infrared characteristics, they differ greatly from one another in their

Two proto-planetaries recently detected with Hubble's WFPC2 instrument are the Cotton Candy *(top)* and Silkworm *(bottom)* nebulae, also known as IRAS 17150–3224 and IRAS 17441–2411, respectively. Both bear a strong resemblance to the Egg Nebula (page 32), suggesting that bipolar morphology is relatively common. These nebulae will exist as proto-planetaries for only about a thousand years. Courtesy the author, Kate Su, and Bruce Hrivnak.

visual brightness. Hrivnak and I were initially puzzled by this, but we realized it could be explained by viewing angle. If the dust shell is not spherically symmetric, a proto-planetary viewed through a thinner part of the shell (face-on) will be visually bright. In contrast, if starlight has to pass through a lot of equatorial dust and suffers many magnitudes of extinction, the edge-on proto-planetary nebula will appear faint at visible wavelengths.

It is desirable to image the actual nebulae around proto-planetaries. But unlike the older planetary nebulae, which are made of glowing plasma ionized by their very hot central stars, the proto-nebulae are not ionized and therefore do not actually radiate at visible wavelengths. Whatever brightness they have comes from starlight reflected off the surrounding dust. A bright central star typically outshines the small, faint nebula.

Using this reasoning, the best bet to find the surrounding nebulosity is from the faint, edge-on systems. In 1991 we attempted to do this using the CFHT's high-resolution camera, which at the time could produce the highest image quality of any ground-based telescope. Two of our proto-planetary candidates, IRAS 17150–3224 and IRAS 17441–2411, showed unmistakable nebulosities with this instrument. In each case the nebula is made up of two lobes with a dark dust lane in the middle. The stars, hidden behind the dust lanes, shine through polar gaps and illuminate the dusty reflection lobes to either side. This discovery confirmed that the Egg Nebula was not unique.



WILLIAM B. LATTER / NASA

NGC 7027 is one of the best-studied planetary nebulae. Its torus of molecular gas (pink) is analogous to the torus crossing the center of the proto-planetary Egg Nebula. However, in that case we see the ring edge on, while in NGC 7027 we see it at approximately a 45° angle. If this nebula were oriented differently, it could closely resemble the Egg!

The HST Era

While we were excited about these images, the next step proved to be more difficult. No ground-based telescope could improve upon our observations, and the Hubble Space Telescope was having its own problems with the spherical aberration of its primary mirror. However, we were fortunate to be awarded observing time with Hubble shortly after corrective optics were installed in 1993.

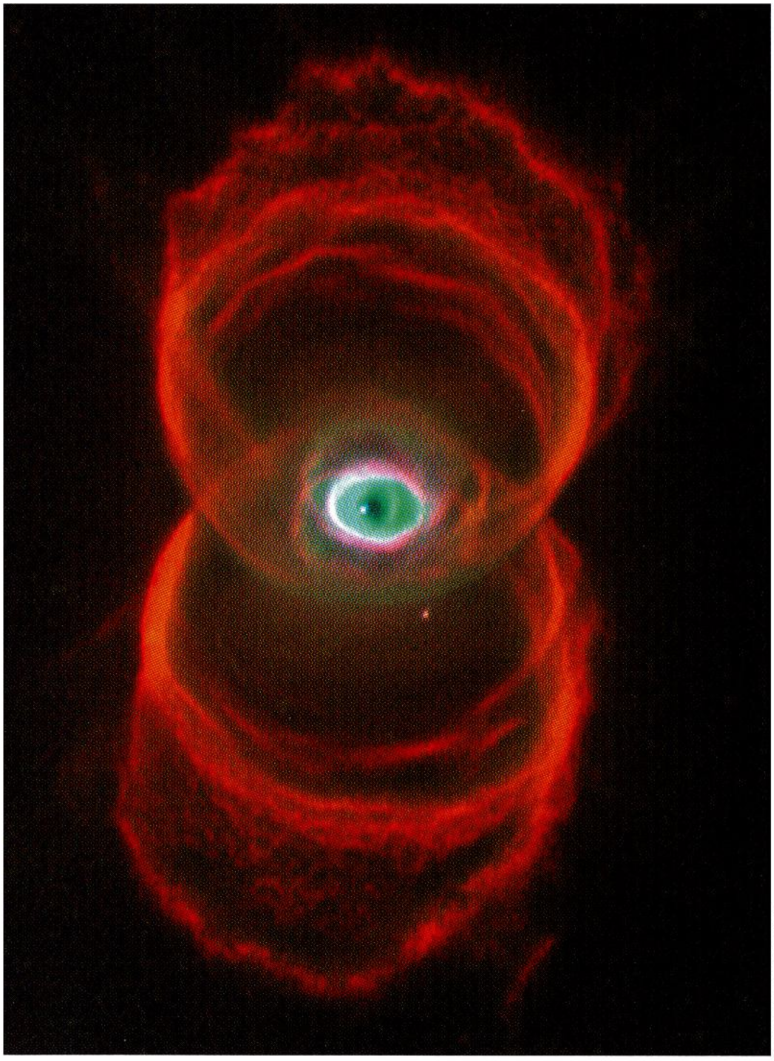
Our HST Wide Field and Planetary Camera 2 images of IRAS 17150–3224 and IRAS 17441–2411 are shown on the facing page. In each case, we can see a series of concentric rings, representing the "puffs" given off by the star in the last few thousand years of its life. After a number of these puffs, the star is wrapped inside a cocoon. In the HST images we are seeing the first indication that the nebulae are emerging from their cocoons, like butterflies undergoing metamorphosis. These two nebulae were named the Cotton Candy Nebula and the Silkworm Nebula, respectively. While "cotton candy" gives a fair description of the first nebula's texture, the name Silkworm is particularly appropriate because it gives the correct scientific connotation.

Further images of the Egg obtained with HST's Near Infrared Camera and Multi-Object Spectrometer (NICMOS) have recently revealed an equatorial torus made up of molecular hydrogen. This confirms that most of the circumstellar material lies in the equatorial direction, and the bright lobes represent the polar openings of the cocoon. The brightest parts of the nebula are in fact located where there is the least amount of matter!

The Birth of Planetary Nebulae

Since the 1918 publication of the first planetary nebula atlas by Heber Doust Curtis, astronomers have been puzzled by the morphological variety and richness of these objects. Now with proto-planetary nebulae we have the opportunity to witness the origin of such morphologies. The cocoons created in the red-giant stage are roughly spherical, as indicated by the circular rings seen in the Cotton Candy and Silkworm nebulae. Yet planetary nebulae often have bipolar shapes. How does this transformation occur?

The answer may lie in the interacting-winds theory. This idea was first proposed by myself, Chris Purton (then of York University) and Pim FitzGerald (University of Waterloo) in 1978 to address the origin of planetary nebulae (*S&T:* July 1996, page 38). Planetary nebulae were once believed to be abruptly ejected red-giant atmospheres, but no theory successfully explained how such an event might take place. The



R. SAHAI AND J. TRAUGER

Like the other WFPC2 images of planetary nebulae in this article, this color picture of MyCn 18, the Hourglass Nebula, is a composite of three exposures taken with different filters. In this case ionized nitrogen is colored red, ionized hydrogen is green, and doubly ionized oxygen is blue.

SOME ASTRONOMERS BELIEVE THAT PLANETARY NEBULAE ARE SHAPED BY COMPANION STARS OR PLANETS

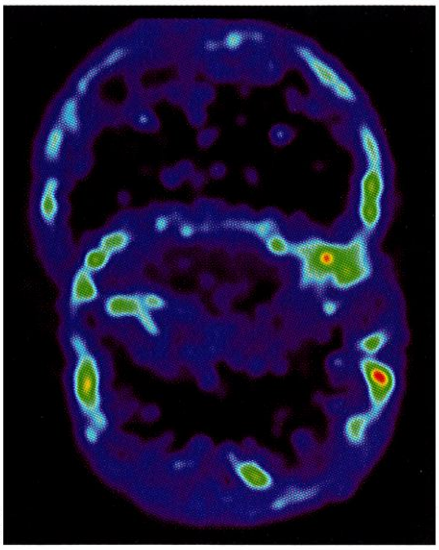
discovery of circumstellar shells around red giants convinced me that the shells must have an effect on the formation of planetary nebulae. Our calculations showed that a hypothetical fast wind from the central star could compress and accelerate the circumstellar material (ejected earlier in a slow wind) into the shell shapes found in planetaries. This prediction was confirmed by the International Ultraviolet Explorer satellite, which found that many central stars of planetary nebulae in fact have fast winds. Subsequently Bruce Balick (University of Washington) successfully applied the interacting-winds theory to explain the morphology of planetary nebulae. Any slight asymmetry in the red-giant envelope can be amplified by the fast wind and create the bipolar morphologies so often observed in planetaries. A simulated planetary-nebula image using the interacting stellar winds model is shown below. It can explain even the most peculiar morphology, such as that of the Hourglass Nebula at left.

The origin of this asymmetry is a topic of high current interest and controversy. Some astronomers, such as Noam Soker (University of Haifa) and Mario Livio (Space Telescope Science Institute), believe that the asymmetry is caused by the influence of companion stars or planets (*S&T:* November 1997, page 20). Other than the cause of this asymmetry, the fundamental question is: when does the fast wind begin to shape its surroundings? In images of proto-planetary nebulae we are probably seeing the fast wind beginning to punch two holes through the weakest parts of the cocoon and allowing the "butterfly" to escape. If these proto-planetary nebulae left the red-giant phase only a few hundred years ago, then the interacting-winds process must already be at work.

The connection between proto-planetary and planetary nebulae can be seen in the HST image of Hubble 5 (page 33). Again, we see two bipolar lobes and faint, concentric rings, but this time in a mature planetary nebula. A molecular torus similar to that observed in the Egg Nebula has been found in the planetary nebula NGC 7027, shown on page 35. NGC 7027 is the best-observed planetary nebula, with more than 1,000 emission lines identified in its spectrum. As such, it probably holds a record among celestial objects. The similarity of NGC 7027's molecular torus to that of the Egg Nebula again points to the influence of orientation. If NGC 7027 were oriented more edge-on, it would probably look like the Egg!

We are blessed with beautiful pictures of the Egg, the Cotton Candy, and the Silkworm because in each case the dust torus blocks off all the starlight. If these objects were turned just 10° or 20°, the central stars would be so bright that the nebulae would be unobservable! In fact, the central star of the Egg Nebula would be a naked-eye object.

While planetary nebulae have been well-known objects for more than 200 years and have fascinated generations of astronomers, the nature of their immediate progenitors was not known until recently. At last, we are now filling in this missing link in our understanding of stellar evolution.



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A simulated image of a planetary nebula calculated using the interacting stellar winds model. It successfully reproduces the two-ring structure seen in the Hubble image of the Hourglass Nebula above.

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