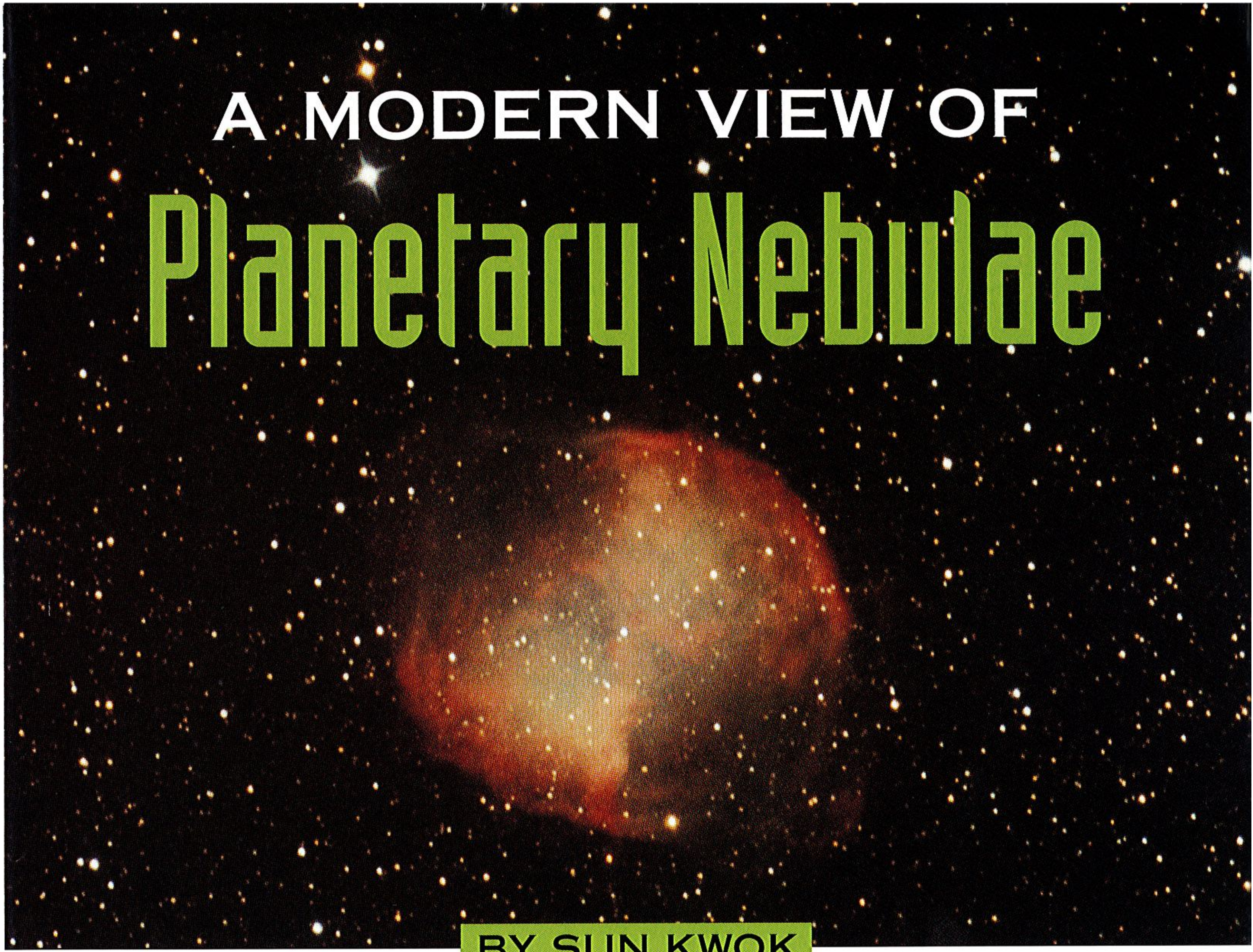
A MODERN VIEW OF Planetary Nebulae



BY SUN KWOK

EVER SINCE William Herschel began calling some disklike, fuzzy patches of light "planetary nebulae," these objects dotting the night sky have been favorite targets of both professional and amateur astronomers. They were among the first of the Milky Way's nebulae to be extensively studied, particularly after the introduction of spectrographs at the end of the 19th century. The spectra of planetaries reveal a rich collection of atoms and ions, including some that emit radiation not seen in laboratories on Earth. Planetary nebulae have thus long served as useful laboratories in which to study exotic atomic processes.

Our theoretical understanding of planetary nebulae began in 1956 with the work of Josif S. Shklovsky. He noted similarities between white dwarfs and the hot, central stars of planetaries, correctly determining that the former evolve from the latter after losing their surrounding nebulae. Although not certain about the details, Shklovsky argued that the nebulae must have been ejected from large stars, probably red giants. This view was supported by the work of George Abell and Peter Goldreich (then at the University of California, Los Angeles), who in 1966 noted the similarity between the expansion velocity of planetaries and the escape velocity of red giants.

As we will learn below, the details are now being brought into focus with tools ranging from orbiting observatories to high-speed computers.

Planetaries, the classical objects that were once believed to be well understood and of little interest, have achieved new, major roles in our quest to understand the large-scale structure of the universe.

PLANETARY NEBULAE: HOT OR COLD?

Planetaries are among the brightest nebulae known. Unlike stars, which radiate in a continuum across the visible spectrum, the light emitted by a planetary is made up entirely of atomic lines, not unlike that from fluorescent or neon lights. A nebula consists of ionized gas, so electrons flow freely among naked protons. However, the capture of an electron by a proton to form a hydrogen atom produces a series of bright emission lines (such as the red hydrogen-alpha line at 6563 angstroms) in a planetary nebula's spec-

One of the most easily recognized planetaries is distinctive M27, the Dumbbell Nebula, in Vulpecula. In October 1995 Dominique Gering of Liège, Belgium, took this 15-minute exposure using a 1-meter telescope and Fujicolor 400 film.

trum. Furthermore, several heavy elements like oxygen, nitrogen, and sulfur also have strong emission lines that result from collisions with electrons.

Since planetaries are so bright and easy to observe, astronomers became overconfident, thinking they knew nearly everything about these objects. Faith in our observational knowledge was first disturbed in 1967. Using a new infrared detector, astronomers at the University of Minnesota found that a small, unremarkable planetary called NGC 7027 in Cygnus (shown on page 41) is extremely bright in the infrared. In fact, the amount of energy this object emits as "heat" far exceeds its output at visible wavelengths. A huge amount of dust must therefore surround the nebula, absorbing the visible light and reemitting the energy in the infrared.

Because of the planetary's hot and hostile environment (the prevailing average temperature hovers around 10,000° Kelvin), astronomers were confident that all nebular matter must be ionized and that molecules, which require a more moderate environment to survive, could not possibly exist. That all changed when Stuart Mufson and his colleagues at the University of Indiana, with the National Radio Astronomy Observatory (NRAO) 12-meter millimeter-wave telescope at Kitt Peak, discovered carbon monoxide in NGC 7027. Many more molecular discoveries followed. In fact, NGC 7027 is now considered one of the richest repositories of molecules in the Milky Way. Soon, planetaries were known to have not only a hot, ionized gaseous component — which biased our view for almost 100 years — but also a cooler side made up of dust and molecules. Our conventional picture of planetary nebulae was badly shaken.

THE ORIGIN OF PLANETARY NEBULAE

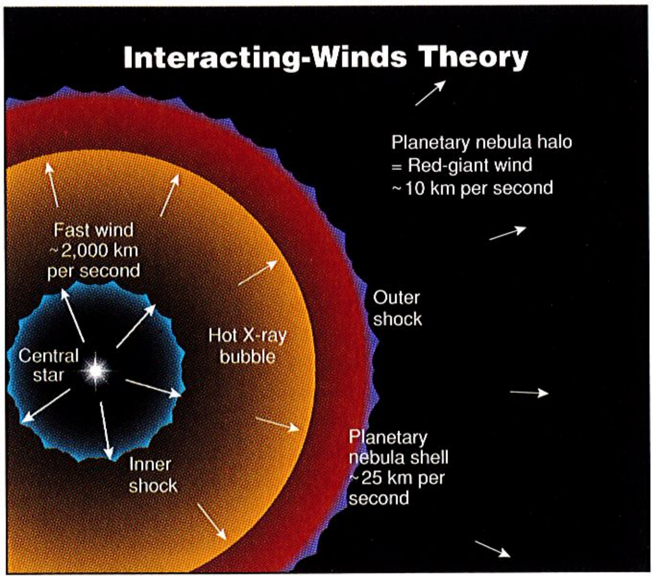
In the mid-1970s, while working at York University, the author noted that NGC 7027 had many similarities to the red giants he had worked on while a graduate student at the University of Minnesota. In particular, the dusty red giant CW Leonis was found in 1971 to have carbon monoxide in its circumstellar envelope by Philip Solomon (then at the University of Minnesota). Many red giants, it soon became known, have similar characteristics.

Could there be a connection? The circumstellar envelopes of red giants are hollow and round, whereas planetaries have ring shapes and much higher densities. Furthermore, the nebulae expand much faster than red-giant envelopes. Clearly a connection is plausible, but it is not just a question of the one gradually diffusing into the interstellar medium and becoming the other. Some mechanism is needed to compress and accelerate the nebulae.

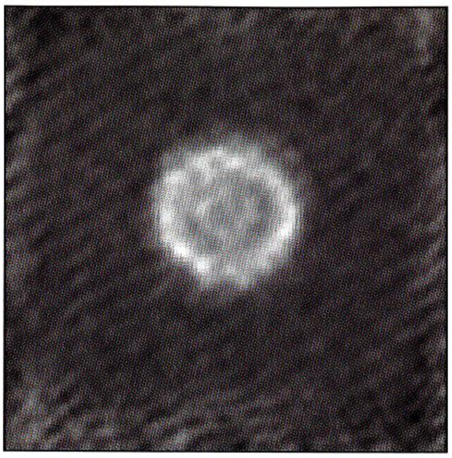
The solution is the interacting-winds theory, proposed in 1978 by the author, Chris R. Purton, and M. Pim FitzGerald. Red-giant envelopes are built up over about a million years via a slow stellar wind. If this wind entirely depletes the red giant's atmosphere, a hot core will be exposed. The fast stellar wind that is hypothesized to emerge from this core acts as a snowplow when it encounters the material expelled from the red giant. That material is then swept up into a dense nebula — the planetary — while the much larger red-giant envelope remains beyond. Because the outer material has a much lower density and is outshone by the dense inner nebula, the envelope is difficult to detect.

Observational confirmation of the interacting-winds theory came quickly. In December 1978 the International Ultra-

Shapley 1 in the southern constellation Norma has a remarkably spherical nature that is unusual among planetary nebulae. A shell of dust and gas 76 arcseconds across surrounds the 14th-magnitude central star. Copyright Anglo-Australian Observatory.



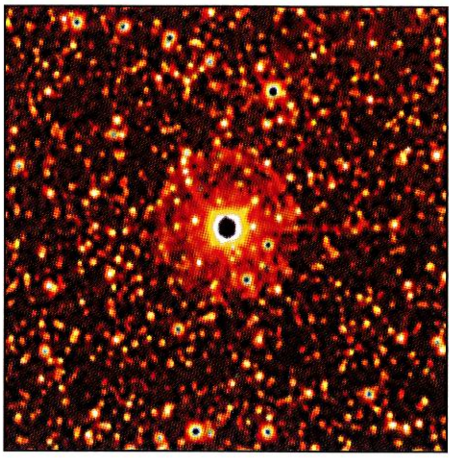
When a low-mass star like the Sun reaches the end of its hydrogen-burning life, it swells into a red giant that slowly ejects its atmosphere. A fast wind then emerges from the exposed stellar core. A planetary nebula is born when this fast wind plows into the previously ejected material, leaving behind a hot bubble of rarefied, X-ray-emitting gas.



At visible wavelengths, planetary nebula K3-62 in Cygnus looks like an ordinary star. However, astronomers using the Very Large Array radio telescope at a wavelength of 3 centimeters resolved the 2-arc-second-wide nebula. Courtesy Sun Kwok.

violet Explorer (IUE) satellite carried into space the first major telescope capable of ultraviolet spectroscopic measurements. One of the first discoveries from IUE, made by Sara Heap (NASA/Goddard Space Flight Center), was that fast stellar winds indeed flow from the central stars of planetary nebulae.

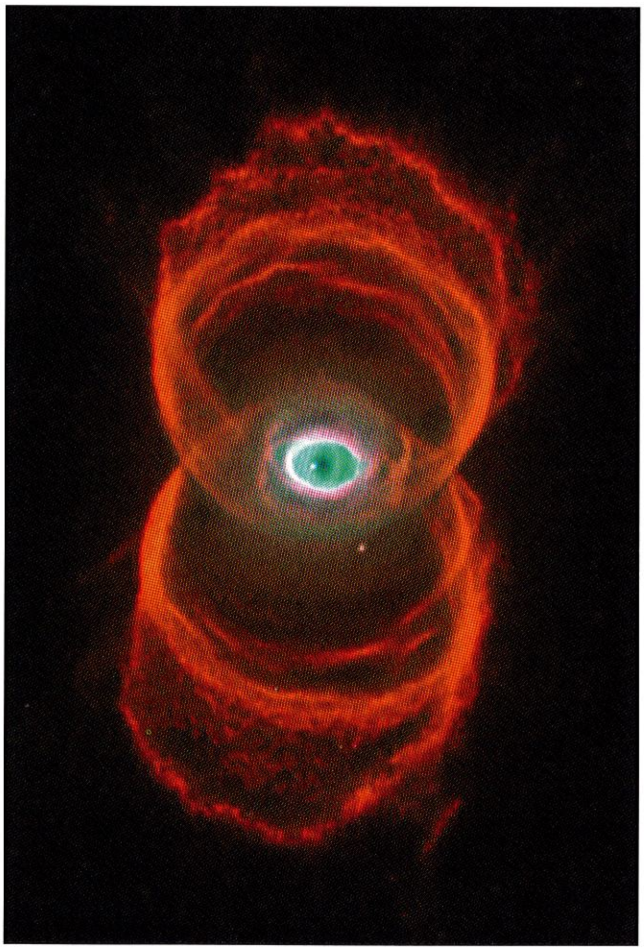
Then You-Hua Chu (University of Illinois) and George Jacoby (Kitt Peak National Observatory) made use of the great dynamic range of CCD cameras, which allows the measurement of faint objects in the vicinity of bright ones, to discover that many planetaries have faint halos. Although some were previously known from photographic plates, these observations demonstrated that they are the rule and not the exception. Bruce Balick (University of Washington) also took some very spectacular pictures of planetary halos using the KPNO 2.1-meter telescope (*S&T:* October 1991, page 347). One example is shown at right. The common presence of these halos — the remnants of the red-giant envelopes — further bolsters the interacting-winds theory for planetary-nebula formation.



Faint halos around planetary nebulae, such as this one seen around compact NGC 6803 in Aquila, are clear indicators of the red-giant past of their central stars. This hydrogen-alpha image was taken at Kitt Peak National Observatory by Bruce Balick.

SHINING FROM RADIO TO X-RAY

Planetaries have long been known as radio sources, thanks to the radiation generated when unbound electrons brush past protons. The modern technique of aperture synthesis, which uses an array of radio telescopes to simulate an extremely large dish, is capable of producing pictures with very high angular resolutions compared to that usually possible at visible wavelengths. The Very Large Array (VLA), completed in 1980, was used by teams from Groningen and Calgary universities to map planetary nebulae. With a resolving power of 0.1 arcsecond, the VLA has been particularly successful in resolving many planetaries that appear as featureless points in visible light. A striking example is shown at upper left.



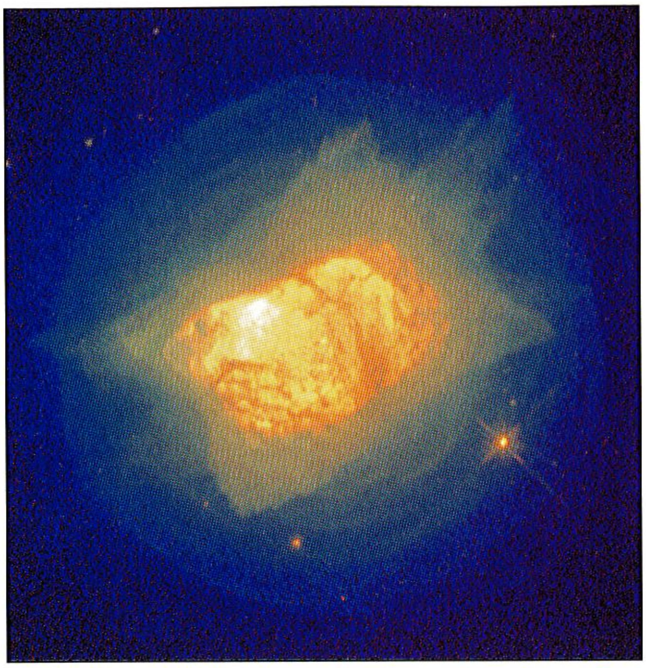
Dubbed the Etched Hourglass Nebula by the astronomers who imaged this object with HST, MyCn18 in Musca is a striking example of the exotic shapes planetaries can develop. A dense cloud of dust girdling the central star's equator may have thwarted expansion, resulting in a pinched waist. Courtesy Raghvendra Sahai, John Trauger (Jet Propulsion Laboratory), and the Space Telescope Science Institute.

The space-based telescopes launched in the last two decades have also greatly expanded our knowledge of planetaries in other parts of the electromagnetic spectrum. The 1983 launch of the Infrared Astronomical Satellite (IRAS) gave us the first opportunity to survey the far-infrared sky, which cannot be observed from Earth. In its 10-month lifetime, it detected more than a quarter-million far-infrared sources. More than a thousand of these are previously known planetaries.

Since the total number of known planetaries is only about 1,500, this high detection rate shows that NGC 7027's strong infrared emission is not exceptional. Many planetaries, young ones in particular, are still shrouded in the dusty envelopes of their red-giant progenitors. These nebulae were not found earlier because their dust grains are so cold they radiate at wavelengths too long to be detected by ground-based instruments. When the IRAS data were analyzed, most of the energy emitted by young planetaries was found to lie in the infrared portion of the spectrum. Until then, we had badly underestimated their energy output.

The large amounts of cold dust inferred from IRAS's pioneering observations have now been corroborated by the Infrared Space Observatory (ISO), launched last November by the European Space Agency (*S&T:* February issue, page 11). For the first time, astronomers now have spectroscopic capability in the far infrared. Planetary nebula NGC 6543 in Draco was one of the first objects observed by ISO's spectrometers. Copious quantities of dust at temperatures near 100° K are evinced by a broad thermal emission feature peaking around 30 microns.

Another prediction of the interacting-winds theory is being investigated by the X-ray-sensitive Rosat satellite (*S&T:* August 1995, page 35). Shock waves generated by the colliding winds are believed to produce a hot bubble inside the planetary nebula. With a temperature of millions of degrees, this bubble radiates X-rays. Rosat detected several planetaries, making them one of the few classes of celestial objects that are active in every part of the electromagnetic spectrum.



NGC 7027 in Cygnus was the first planetary discovered to radiate much more strongly in the infrared than at visible wavelengths. In this Hubble Space Telescope image the planetary nebula (bright orange) is at the center of an extended, round halo. NGC 7027's central star is a tiny yellow spot at the nebula's center. This young white dwarf's previous incarnation as a pulsating red giant is revealed by concentric shells in the outer halo. The planetary itself is about 10 arcseconds across. Courtesy Howard Bond and the Space Telescope Science Institute.

AN ASTRONOMICAL COINCIDENCE?

According to the latest catalog of planetaries compiled by Agnès Acker (Strasbourg Observatory), approximately 1,150 such objects exist in our galaxy, with another 350 candidates awaiting confirmation. However, galactic-dust extinction and the lack of an all-sky survey for planetaries suggest that this number is far from complete. In fact, the Milky Way's planetary-nebula population has been estimated to be at least 10 times higher. Planetaries are likely a common phenomenon, yet the question of why they exist at all has rarely been raised. The answer is not as straightforward as it may seem.

A planetary derives all its energy from its central star. Ultraviolet radiation from that star ionizes the surrounding nebular material, which reradiates the energy as visible light. Some of this light is absorbed by dust, which downgrades the photons into the infrared. Without a hot star the surrounding nebula would be dark and invisible. To emit enough ultraviolet photons, a central star must have a minimum temperature of 30,000° K (though temperatures as high as 200,000° K have been detected).

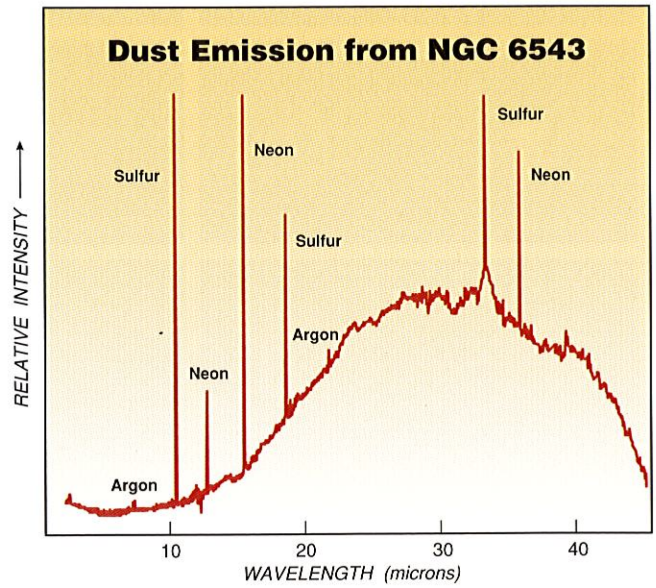
The existence of planetaries therefore relies on two factors: a hot star and a cloud of gas and dust nearby. The gas and dust are around for only a few tens of thousands of years, after which the cloud disperses and becomes part of the interstellar medium. The red-giant core has to evolve from a cool (3,000° K) star to a hot (30,000° K) one in the same time frame. If it evolved too slowly, the nebula would be gone before it could be lit up by the star. If the star evolved too quickly, the lifetimes of planetaries would be very short and their numbers at a given time would be much fewer. In other words, for planetaries to exist as we find them, stars and their nebulae have to evolve in step with each other. This concept was proposed by Bohdan Paczynski (then at the Copernicus Astronomical Center).

In the early 1980s, Detlef Schönberner (University of Kiel) performed detailed stellar-evolution calculations that outlined the conditions necessary for the central star to evolve as required. One of these is a stellar wind, to help the star lose mass and evolve faster. Therefore the fast wind envisioned by the interacting-winds model serves not only as an agent to compress and accelerate the nebula but also to keep the evolution of the star in step.

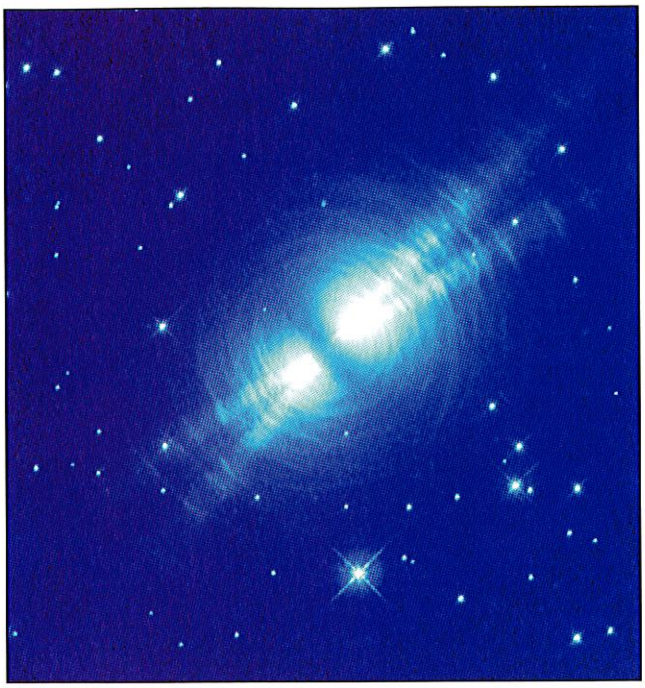
HOW FAR ARE THEY?

Our estimate of the galaxy's total population of planetary nebulae depends much on our ability to estimate their distances. For example, if all the known planetaries are relatively nearby, there have to be many more in the rest of the galaxy; if they are far away, by contrast, the total population may be small.

Distance determination is a widespread problem in astronomy. The sky we face is two-dimensional, so that any information regarding the third dimension, distance, has to be inferred. The most common way of doing so is by using the inverse-square law: the apparent brightness of a celestial object will drop by a factor of four when its distance is doubled. If an object's *intrinsic* brightness is known, its *observed* brightness indicates its distance. For many



This infrared spectrum of NGC 6543 in Draco was recently obtained by the Infrared Space Observatory's Short Wavelength Spectrometer. Various metal emission lines can be seen on top of the strong dust continuum, which is a trademark feature of planetaries. Courtesy the European Space Agency.



The Egg Nebula in Cygnus is probably the most famous example of a protoplanetary nebula — the crucial transition from red giant to planetary. A disk of dust can be seen separating the two lobes of reflected visible light. The origin of the nested shell-like structures is not clearly understood, but it may be related to the sporadic mass-loss history of the nebula's progenitor star. This red-light image by Raghvendra Sahai and John Trauger (Jet Propulsion Laboratory) is courtesy the Space Telescope Science Institute.

years astronomers relied on a variation of this theme, known as Shklovsky's method, to determine distances to planetaries.

Instead of assuming all planetaries possess the same intrinsic brightness, Shklovsky assumed that they have the same mass. When the nebula expands as it ages, its density decreases, which in turn leads to a drop in the brightness of recombination lines and other radiation characteristic of ionized gas. Since the angular size of the object is related to its physical size and distance, measuring a nebula's recombination-line strength and its angular size allows the determination of its distance.

This view was challenged by Stuart Pottasch (University of Groningen). He suggested that not all planetaries are totally ionized, so the ionized mass used in Shklovsky's method cannot be the same from planetary to planetary. In fact, Pottasch provided evidence that the ionized fractions within planetaries range over a factor of a thousand. Using the planetary nebulae in the Magellanic Clouds (which have known distances) as a sample, Peter Wood of Mount Stromlo and Siding Spring observatories also confirmed this effect. Pottasch's view is supported by the direct detection of molecular material in NGC 7027; less than 10 percent of that nebula's total mass is now thought to be ionized.

With the improved stellar-evolution tracks provided by Schönberner, we now know that the central stars of planetaries evolve rapidly and emit varying amounts of ultraviolet photons over their lifetimes. Since the ionization of a nebula depends on this output, the ionized-mass fraction must change with the star's age. The interacting-winds model further weakens Shklovsky's method by implying that the nebular mass also changes with time as more and more material is swept up by the stellar wind.

Unfortunately, though many schemes have been put forward to replace Shklovsky's method, there is no foolproof way to determine the distances to planetary nebulae. This remains a major problem facing astronomers today.

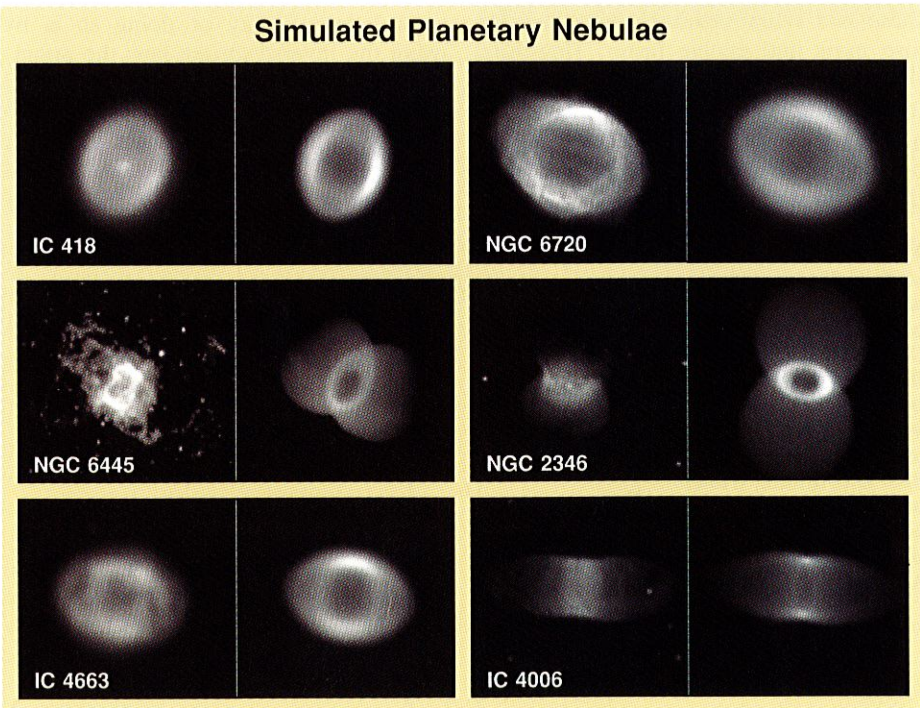
A MORPHOLOGICAL MENAGERIE

One of the most interesting aspects of planetaries, as well as one that backyard astronomers can observe directly, is their diverse morphologies. Curiously, only a few planetaries are round. If the nebulae originate from the mostly spherical circumstellar envelopes of red giants, why do planetaries develop strange forms? The presence of a companion star may certainly influence the development of some planetaries like the Southern Crab (*S&T:* December 1989, page 571), but many of these objects have clearly come from solitary stars.

Not surprisingly, stellar winds play a central role in shaping planetary nebulae. Balick grouped the different morphologies of planetaries into an evolutionary sequence by considering phases in a low-mass star's mass-shedding career (*S&T:* February 1987, page 126). The work resulted in two doctoral theses, one by Adam Frank at the University of Washington and another by Garrelt Mellema at the University of Leiden. Their simulated images are difficult to distinguish from the real objects in the sky.

THE MISSING LINK

According to Schönberner's work, a gap of about 3,000 years exists between the end of the red-giant phase and the



Using hydrodynamical calculations and the interacting-winds model, Cheng-Yue Zhang created a series of hypothetical planetary nebulae. Here they are depicted as they would appear in the light of hydrogen-alpha emission *(right)*, with H-alpha images of actual planetary nebulae to their left. Courtesy Cheng-Yue Zhang, University of Calgary.

genesis of a luminous planetary nebula. This is the time required for the star's temperature to increase from 3,000° K to 30,000° K as the hot core is further exposed. Objects in transition, often referred to as protoplanetary nebulae, are a key missing link in our understanding of stellar evolution.

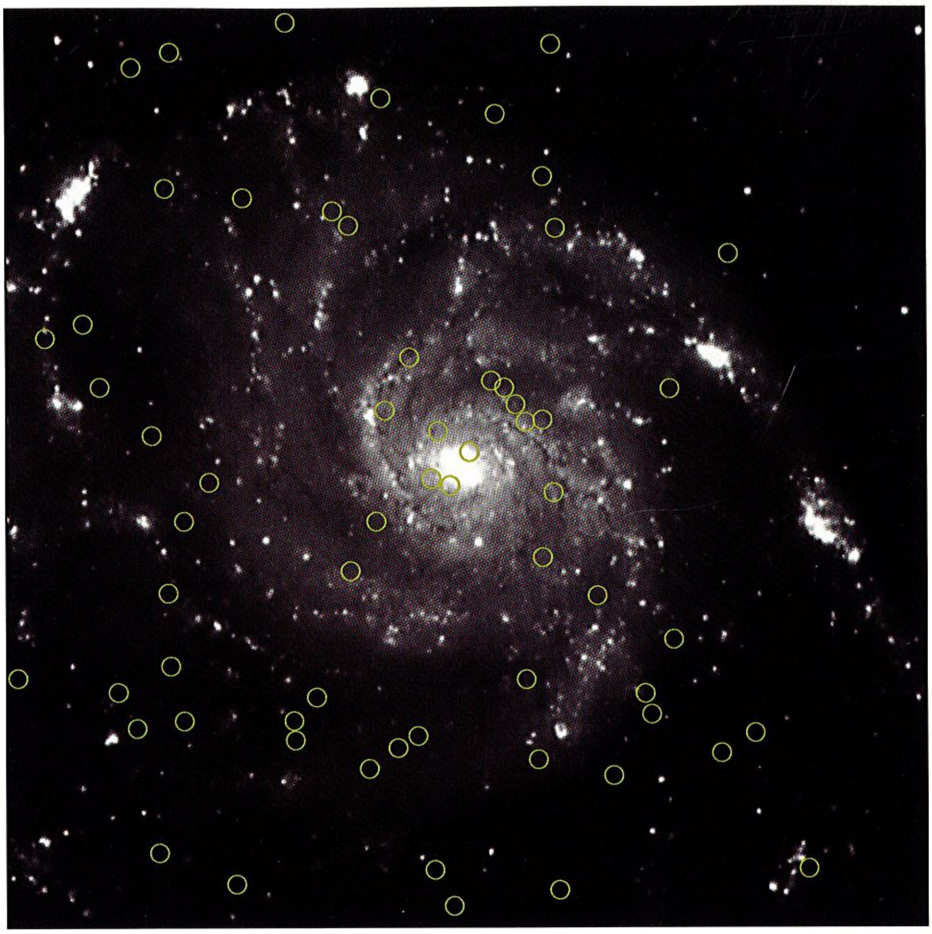
Finding examples of this link at first seemed hopeless. A star at an intermediate temperature would hardly look out of the ordinary. And with only a few hundred expected in the galaxy, protoplanetary nebulae would be impossible to locate among the Milky Way's saturated star fields. Their eventual discovery is a fascinating story whose telling lies beyond the scope of this article. A few dozen such transitional objects are now known. The most famous protoplanetary is the Egg Nebula in Cygnus, shown on the previous page (May issue, page 12). The Hubble Space Telescope captured starlight scattered off dust grains that formed in the progenitor's cool outer atmosphere. The central star itself is obscured by dust farther in.

PLANETARIES AND THE UNIVERSE

Over the past 60 years the size of the known universe has greatly increased — not because the universe has expanded, but because astronomers continue to rethink the value of the Hubble parameter (H_0). This factor, which determines the age of the universe, is calculated from the distances to external galaxies and their observed recession rates, or redshifts. Since astronomers' estimates of extragalactic distances have been extremely poor, the value of the Hubble parameter has changed by a factor of 10 since the time of Edwin Hubble. Even now there are protagonists who favor values that differ by as much as a factor of two.

The solution to this problem is simple in principle. We need to find a "standard candle" that is bright enough to be seen at large distances and yet has a uniform intrinsic brightness. Numerous objects have been used — including Cepheid variables, novae, and supernovae — with varying degrees of success.

The application of planetaries as standard candles was pioneered by George Jacoby. With a narrowband filter to increase the contrast between the nebulae and the background sky, planetaries can easily be isolated and distinguished from stars even in distant galaxies (*S&T:* December 1988, page 605). By examining thousands of planetaries in nearby galaxies, Jacoby and his collaborators found that they have a well-defined luminosity function: planetaries never seem to exceed a certain intrinsic luminosity, even in galaxies of very different types. When he applied this technique to the Hubble-parameter problem in 1990, he derived a value for H_0 much larger than what was then fashionable. His results implied that the universe is only 10 billion years old (*S&T:* November 1990, page 466). Recent HST observations involving of the traditional Cepheid variables have since lent support to Jacoby's results (January issue, page 24).



Planetary nebulae are easily detected in galaxies other than the Milky Way, and their well-defined luminosity function makes them good standard candles. The planetaries in Ursa Major's grand spiral M101 (circled) suggest a distance to that galaxy of 25.1 million light-years. This value is in close agreement with a distance derived from observations of Cepheid variables made by the Hubble Space Telescope. Courtesy John J. Feldmeier, Robin Ciardullo, and George H. Jacoby.

Planetaries are also useful tracers of the most enigmatic component of galaxies: dark matter. Since they exist not only in a galaxy's plane but also in its halo, their orbital motions are affected by normal luminous matter (stars and interstellar gas) as well as by the large amount of invisible dark matter in a halo. With current 4-meter-class telescopes, the velocities of planetaries can be measured with relatively high precision, and the distribution of a galaxy's mass — both luminous and dark — can be traced. Painstaking velocity measurements on planetaries have also allowed astronomers to "weigh" galaxies and their dark-matter halos (*S&T:* December 1994, page 16).

Planetary nebulae, the classical objects that were once believed to be well understood and of little interest, have achieved new, major roles in our quest to understand the large-scale structure of the universe.

Sun Kwok, a professor at the University of Calgary, has published extensively in the field of planetary nebulae. He is currently the chairman of the International Astronomical Union Working Group on Planetary Nebulae.

Further Reading

Balick, Bruce. **"The Shaping of Planetary Nebulae."** *Sky & Telescope,* February 1987, 125–130.

Kwok, Sun. **"Planetary Nebulae: A Modern View."** *Publications* of the Astronomical Society of the Pacific 106 (1994), 344–355.

Soker, Noam. **"Planetary Nebulae."** *Scientific American,* May 1992, 78–85.