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# Mercury

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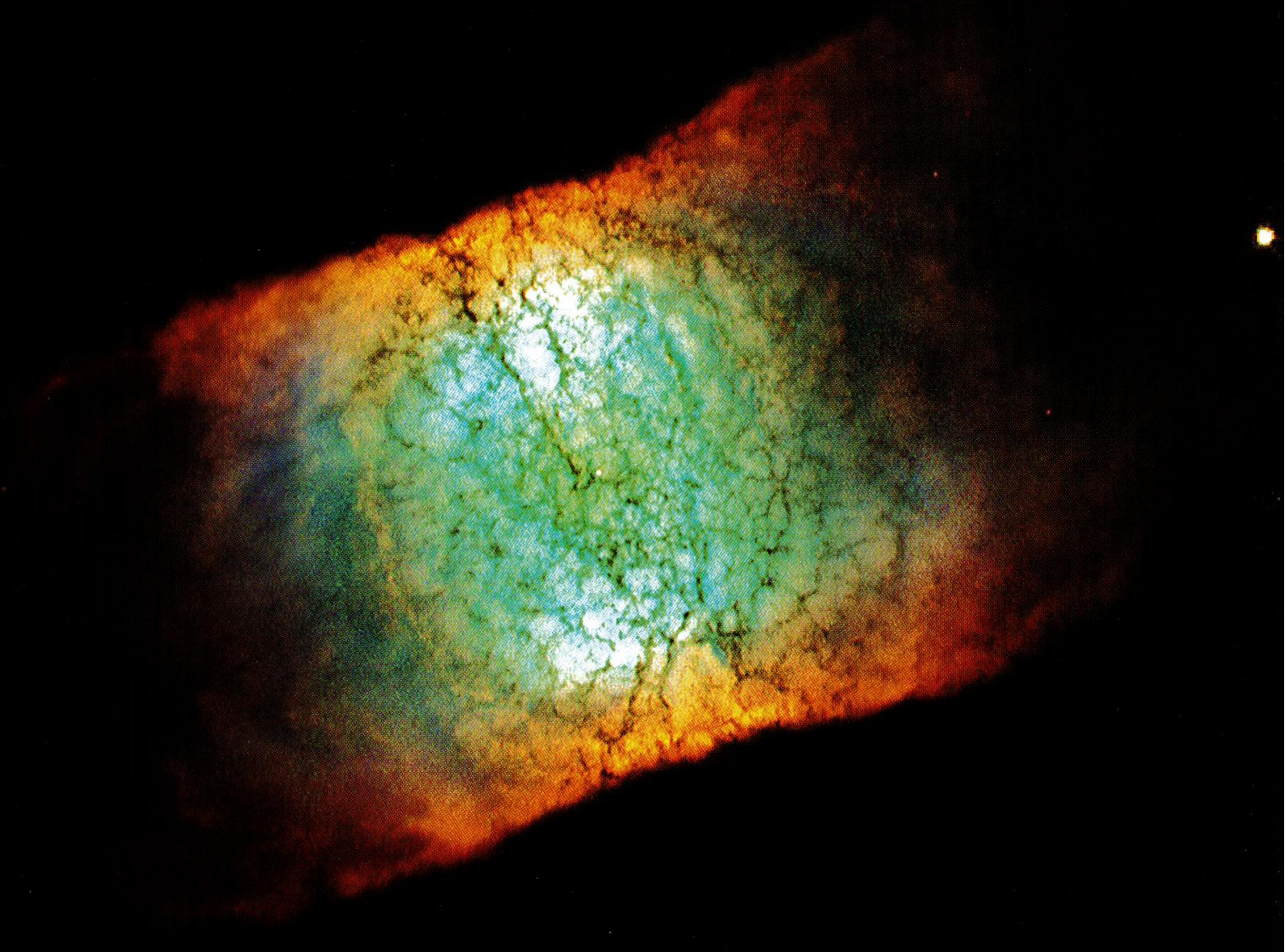

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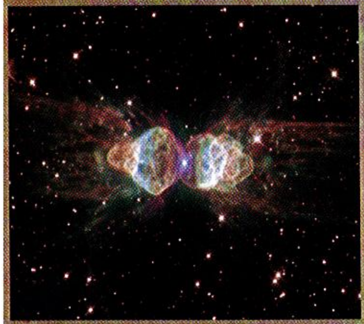
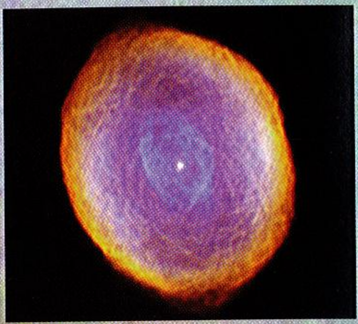
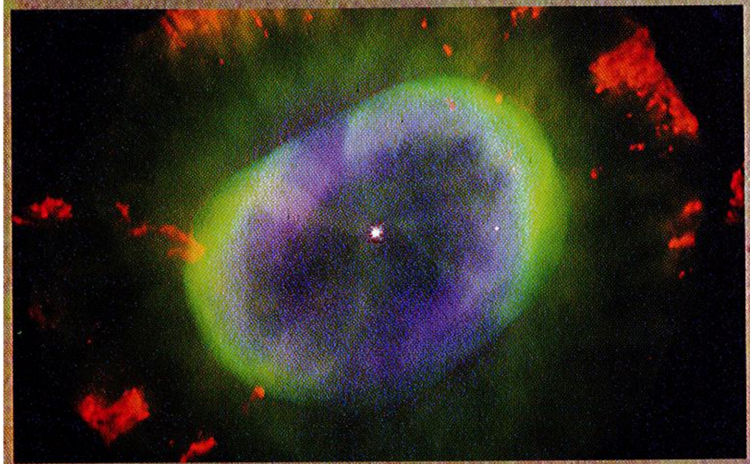
# PLANETARY

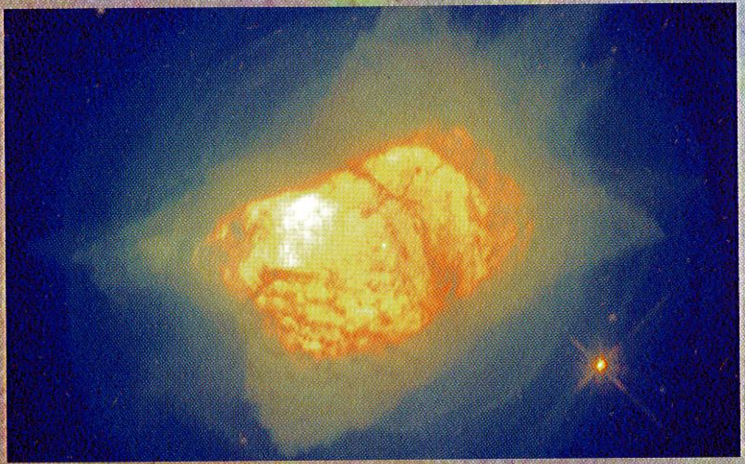

**Menzel 3 (the Ant Nebula).**

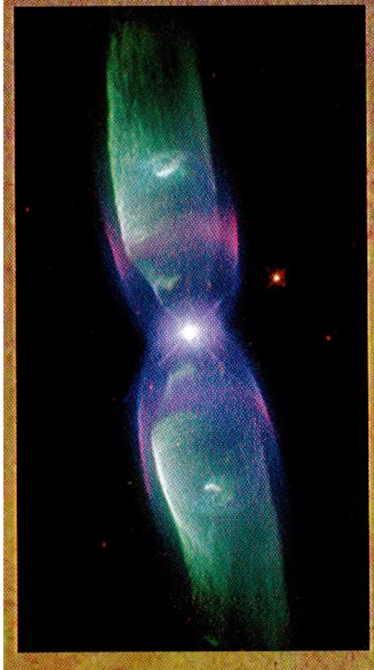

**Hubble 5.**


**NGC 3132 (the Southern Ring).**


**IC 418 (the Spirograph Nebula).**


**NGC 7662 (the Blue Snowball).**


**NGC 7027.**


**Minkowski 2-9.**


**NGC 6537 (the Red Spider Nebula). See page 31 for all the credits for images on this page.**

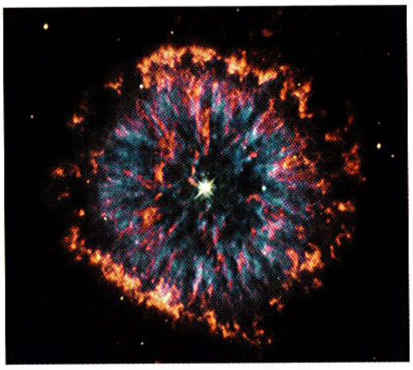
# NEBULAE: Shrouds of Mystery

*To some, planetary nebulae are the prettiest objects in the cosmos. But to the astronomers who study these stellar shrouds, planetary nebulae offer a treasure trove of fascination and mystery.*

**by Sun Kwok**

From a 10-year-old child looking through a backyard telescope to professional scientists using the Hubble Space Telescope, planetary nebulae have been the favorite observing targets of many astronomers. Although we are all fascinated by the magnificent shapes and wonderful colors of planetary nebulae, the journey to understanding their origin and inner workings has been a long and difficult one.

The journey got off to a rough start with William Herschel's unfortunate naming of these objects as "planetary nebulae" for their superficial resemblance to Uranus. Astronomers later associated planetary nebulae with their hot central stars, leading to the erroneous assumption that they are young, because young stars are often hot. In the late 19th century, astronomers found that planetary nebulae spectra are dominated by a pair of bright green lines of unknown origin. This led to the suggestion that these lines were due to an unearthly element called "nebulium" (see "Lighting the Nebulae," page 17). Astronomers abandoned this idea in the 1920s when quantum physics led to the realization that these lines are due to ionized oxygen atoms radiating in near-vacuum conditions.



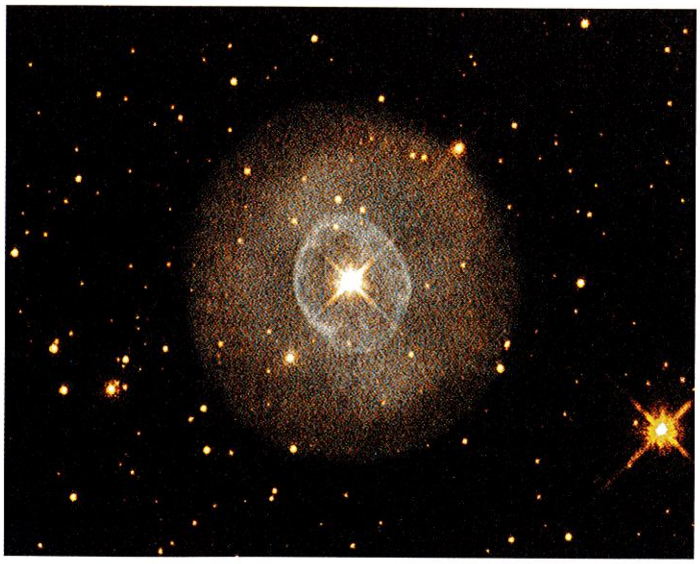
**NGC 6751. Courtesy of NASA and the Hubble Heritage Team (STScI/AURA).**

This identification helped spark a new discipline called "astrophysics," which involves the application of the knowledge of atomic and nuclear physics to the understanding of celestial phenomena. With these new forms of knowledge at their disposal, astronomers in the 1950s were able to interpret the optical spectra of planetary nebulae and to derive their temperature and density conditions. These findings led Soviet astronomer Iosef Shklovskii to propose in 1956 that planetary nebulae represent a phase of stellar evolution that old, evolved stars pass through.

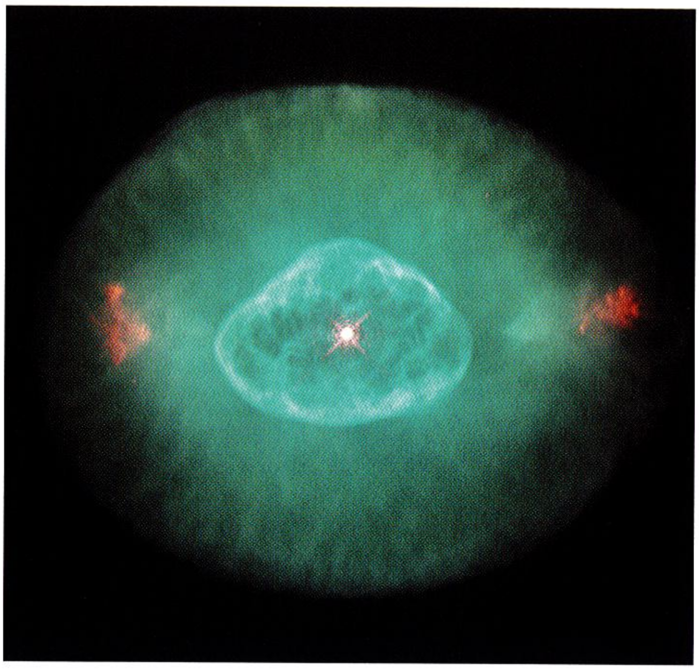
## Emergence from the Dark Ages

Although Shklovskii's qualitative picture was a major breakthrough in our understanding of planetary nebulae, many details remained unknown. By that time, astronomers knew that stars are powered by nuclear fusion, but what kind of nuclear reactions are responsible? Astronomers were fairly confident that planetary nebulae were ejected by their parent stars, but how did that happen?

After many theoretical models and scholarly papers, these questions were finally answered in the 1970s. We learned that the central stars of planetary nebula are powered by the nuclear fusion of a thin hydrogen layer on top of a very small and dense carbon/oxygen core. Contrary to the naïve interpretation that planetary nebulae are the result of impulsive ejections leading to the detachment of the star's outer layers, we now understand that they are the result of a much gentler process. Instead of a sudden ejection, the parent star ejects the mass over hundreds of



**Modern imaging has discovered that planetary nebulae have several layers of shells. An example of such a multiple-shell structure can be seen in this image of NGC 6629 taken by the Hubble Space Telescope. Unless otherwise stated, all images were produced at the Space Astronomy Laboratory of the University of Calgary based on data from the HST archive.**



**This HST WFPC2 image of NGC 6826 shows a pair of FLIERs in red.**

thousands of years. Very late in the star's life, it ejects a much faster stellar wind that sweeps up the gas into a shell. This interacting winds model has become the new paradigm of planetary nebula formation.

A furious amount of work followed in the 1980s and 90s to exploit these new ideas. Theorists produced exhaustive computer models to calculate the evolution of the nebulae and their central stars. These models gave us, for the first time, a quantitative theory that could explain the diverse properties of planetary nebulae. Making use of new technologies like CCD detectors, astronomers rigorously tested the theory's many predictions with high-quality data. With our newly found confidence in theory and the increasing number of planetary nebulae detected in external galaxies, some astronomers expressed sentiments that we had finally achieved the goal that had eluded us for 200 years: a complete understanding of the planetary nebula phenomenon.

But this euphoria turned out to be short-lived. By the late 1990s, space telescopes had greatly expanded observational capabilities. Spectacular images from the Hubble Space Telescope have revealed previously unseen features in the nebulae. And the Infrared Space Observatory, for example, has opened new spectral windows, creating entirely new subdisciplines, such as nebular chemistry.

Beginning in 1967, the International Astronomical Union has held regular symposia on planetary nebulae. The most recent meeting took place in November 2001, in Canberra, Australia. At every symposium, we have witnessed growth in the number of researchers and countries involved in this field. At these gatherings, we have seen long-standing problems resolved and new problems emerging. The Canberra symposium was no exception. Planetary nebulae are now discussed not only for their own sake, but also in connection to meteorites in the solar system on a small scale, and galaxies on a large scale. We are even seeing planetary nebulae being employed as yardsticks to measure the size of the universe as well as scales for weighing dark matter (see "Probing the Universe with Planetary Nebulae," page 29).

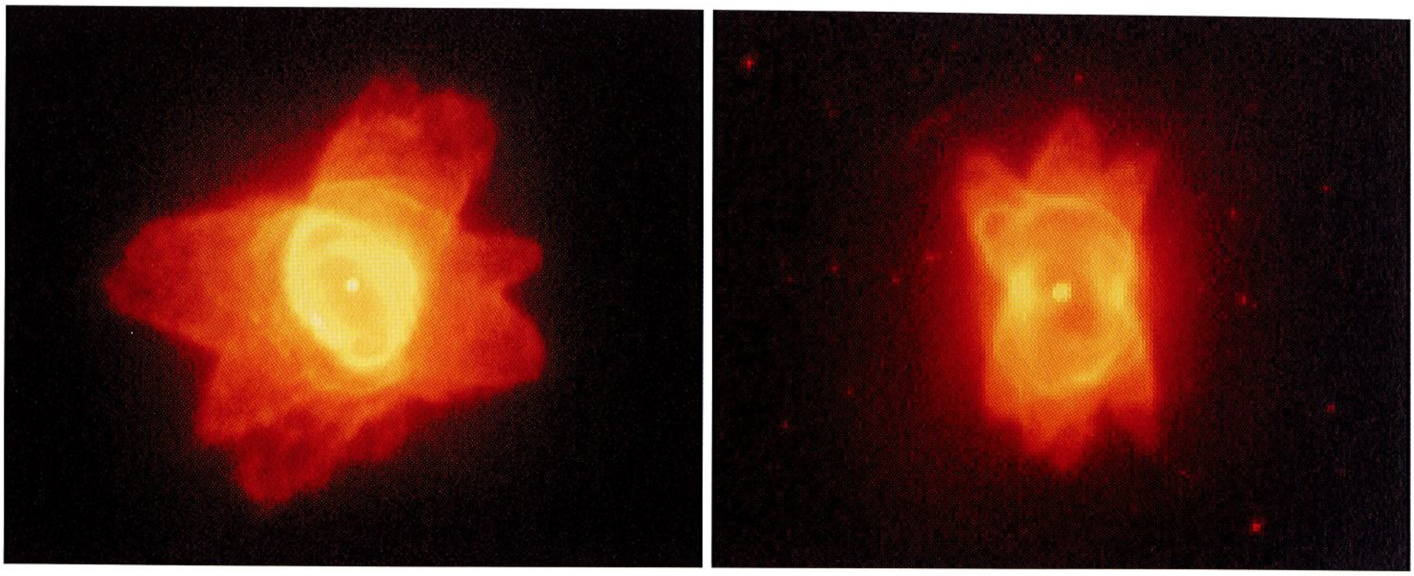
## More Planetary Nebulae

If you want to read more about planetary nebulae and view more beautiful images, you can purchase Sun Kwok's new book, *Cosmic Butterflies: The Colorful Mysteries of Planetary Nebulae* (item BO 264) directly from the ASP catalog by calling **800-335-2624** or by visiting our on-line AstroShop at **www.astrosociety.org**. The ASP catalog also offers a slide set of planetary nebula images compiled by James B. Kaler (item AS 348). Many of the ASP's Hubble Space Telescope slide sets and our Hubble Space Telescope Picture CD (item ST 147) also contain spectacular planetary nebula images.

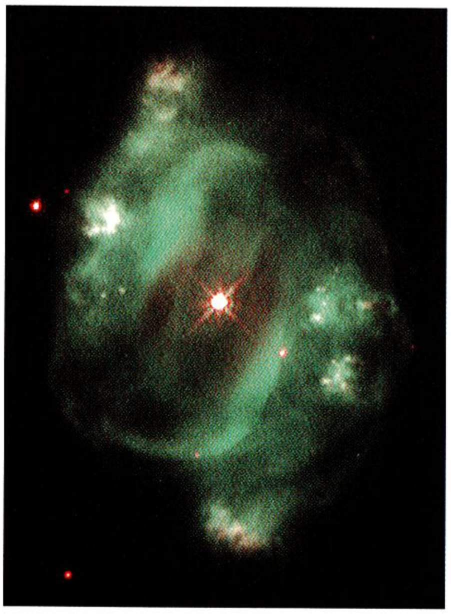
## What Stars Become Planetary Nebulae?

Planetary nebulae represent a brief phase (about 30,000 years) of stellar evolution at the end of a star's life. According to the last planetary nebula catalogue compiled by Agnes Acker of the Observatoire de Strasbourg in 1992, approximately 1,500 planetary nebulae were known in the Milky Way Galaxy. However, as the result of a deep survey of the southern Galactic plane in H-alpha light by the United Kingdom Schmidt Telescope, Quentin Parker and his colleagues have discovered about 1,000 new planetary nebulae, many of them large and faint. In spite of this vast improvement, we believe the actual population of planetary nebulae is much higher, because of the incompleteness of the surveys and viewing obstructions by galactic dust. Our current estimate, still highly uncertain, puts the total number at about 20,000 in the Galaxy.

The combination of the large number of planetary nebulae and their short lifetimes argues that they must be a common phase of stellar evolution. Exactly which mass range of stars will form planetary nebulae is therefore an interesting and pertinent



**Many planetary nebulae have two wings shaped like butterflies, and they are referred to by astronomers as "bipolar nebulae." But "polypolar nebulae" are an entirely new phenomenon. Shown here are two examples, Henize 2-47 and Minkowski 1-37, discovered by the Hubble Space Telescope and dubbed the "Starfish Twins" by Raghvendra Sahai of the Jet Propulsion Laboratory.**



**NGC 5307 is an example of a class of planetary nebulae with bipolar rotating episodic jets (BRETs), a term made up by Alberto López to describe these fascinating objects. Their S-shaped appearance is believed to be created by a precessing jet from the central star acting like a wobbling sprinkler in the center of the nebula.**

question. Even as late as the mid-1980s, most astronomers assumed that only very low mass stars (no more than twice the mass of the Sun) would evolve into planetary nebulae, with more massive stars going supernovae. But infrared observations of the progenitors of planetary nebulae, a class of very luminous red giants called "asymptotic giant branch stars," show that stars born with masses as high as eight times that of the Sun will form planetary nebulae.

Although most astronomers think that the Sun will evolve into a planetary nebula, the experts are less certain. Recent calculations on the evolution of planetary nebulae have suggested that the Sun may evolve too slowly to create the spectacular fireworks that we associate with planetary nebulae. For many years, Volker Weidemann of the Christian-Albrechts-Universität Kiel in Germany has worked on a formula that expresses the mass of a star at the time of its death as a function of its birth mass. In Weidemann's most recent formulation in 2000, he put the Sun at a final mass that just misses the grade, by about half a solar mass. If this is accurate, the Sun will still eject a nebula in about 5 billion years, but it will not be ionized and therefore will not shine on its own; it will only glow dimly in reflected starlight. Because our galaxy has many more low-mass stars than high-mass stars, and Sun-like stars are very common, the question of whether the Sun will form a planetary nebula is more than a concern for the human race, but an important question to answer about galactic evolution.

## Shells, Crowns, and Haloes

Although most astronomers still associate planetary nebulae with a single shell of gas, recent observations, in particular those from the Hubble Space Telescope, have discovered that planetary nebulae have much richer and more complicated structures. In addition to the bright, easily observable shell, they have several fainter layers, some inside and others outside of the main shell. To describe these faint structures, Bruce Balick of the University of Washington has coined terms like "bubbles," "cores," "rims," "crowns," and "haloes."

Astronomers have made tremendous progress in the understanding of the origin of these shells and structures. From dynamical models, Detlef Schönberner of the Astrophysikalisches Institut Potsdam in Germany, Garrelt Mellema of Sterrewacht Leiden in the Netherlands, Adam Frank of the University of Rochester, and others have shown that these shells arise naturally through interacting stellar winds.

When a star enters the later stages of the asymptotic giant branch, it emits a strong, slow wind. This wind drains away so much atmospheric material that the stellar core is eventually exposed. At this stage, the wind becomes thinner but much faster. When this highly supersonic wind catches up with the earlier, slower (but still supersonic) wind, the collision leads to a host of dynamical phenomena, which create shells of different temperatures, densities, and velocities. Because we rarely have the chance to witness such supersonic collisions in our terrestrial laboratories, our ability to compare planetary nebula observations with theory is highly illuminating in our understanding of dynamics.

**These two images show streams of gas that seem to be flowing out of opposite sides of a gun barrel. On the left is the central region of the Rotten Egg Nebula and on the right is Henize 3-401. These bipolar flows are probably being focused by a ring of dust (seen as the dark region between the flows).**

The success of these theoretical models in interpreting these newly discovered structures gives us confidence that our basic scenario for planetary nebula formation is correct. But current theories cannot explain everything. In addition to shell structures, planetary nebulae also possess a range of substructures that can only be described as bizarre. Many have jets moving at hundreds of kilometers per second. Others have pairs of gaseous knots called "FLIERs" that lie symmetrically outside of the main shell. Some have twisting and turning outflows called "BRETs," and others possess sets of regularly spaced, perfectly circular arcs that lie across the nebulae. In the nearby Helix Nebula, the Hubble Space Telescope has detected hundreds of comet-shaped knots, and probably thousands are present. A number of planetary nebulae exhibit pairs of two-dimensional "smoke rings" that are layered one upon another. These discoveries tell us that we still have not figured out many details of planetary nebula dynamics.

Even objects that have been extensively observed over the years are not immune to unexpected discoveries. Astronomers have exhaustively studied NGC 2440 in Puppis, and yet Alberto López of the Universidad Nacional Autónoma de México discovered that this nebula has two pairs of lobes rather than the normal single pair. The Hubble Space Telescope has found many more examples of such "polypolar" nebulae.

The existence of "polypolar nebulae" indicates that the fast winds can be highly directional and focused. How are these outflows confined within a narrow ejection angle? Some astronomers have suggested that if the nebula's central star is in a binary system, the central star's strong gravity could capture some of the companion's mass to create a disk. This disk can then act like a nozzle that funnels the dying star's outflow in certain directions. Magnetic fields also have focusing powers and could be involved in the collimation process. Astronomers are hotly debating these possibilities and no consensus has yet emerged. Because astronomers suspect that similar dynamical processes are also at work in supernovae, star formation, and active galactic nuclei, the lessons that we learn from planetary nebulae are of the utmost importance.

## Shining from Radio to X-rays

One of the most exciting developments in the past decade has been the use of space-based telescopes to perform observations that are impossible from the ground. Earth's atmosphere is opaque to X-rays, ultraviolet light, and most wavelengths of infrared light, so our past planetary nebula studies have been based primarily on visible and radio observations. Like blind men trying to figure out the shape of an elephant, we had an incomplete picture of these objects. Recent observations by the Infrared Space Observatory, the Far Ultraviolet Spectroscopic Explorer, and the Chandra X-ray Observatory have opened our eyes. We now realize that planetary nebulae have million-degree bubbles of gas that shine brightly in

**Circular concentric arcs, like the ones seen here in the Cotton Candy Nebula, are now detected in many planetary nebulae and protoplanetary nebulae by the Hubble Space Telescope. The arcs are ejected at regular intervals of a few hundred years. No successful model has yet been offered to explain the origin of these arcs.**

# Probing the Universe with Planetary Nebulae

The determination of distances to external galaxies has always been a difficult problem, and yet distance measurements are central to our estimation of the universe's age and expansion rate.

About 10 years ago, George Jacoby of the National Optical Astronomy Observatory and Robin Ciardullo of Penn State University pioneered the technique of using planetary nebulae as standard candles for distance measurements. Planetary nebulae radiate most of their visible light in a few strong emission lines, and therefore they can easily be distinguished from ordinary stars. By observing hundreds of planetary nebulae in nearby galaxies, Jacoby and Ciardullo found that the luminosity of planetary nebulae in the ionized oxygen line has a sharp cutoff in the bright end.

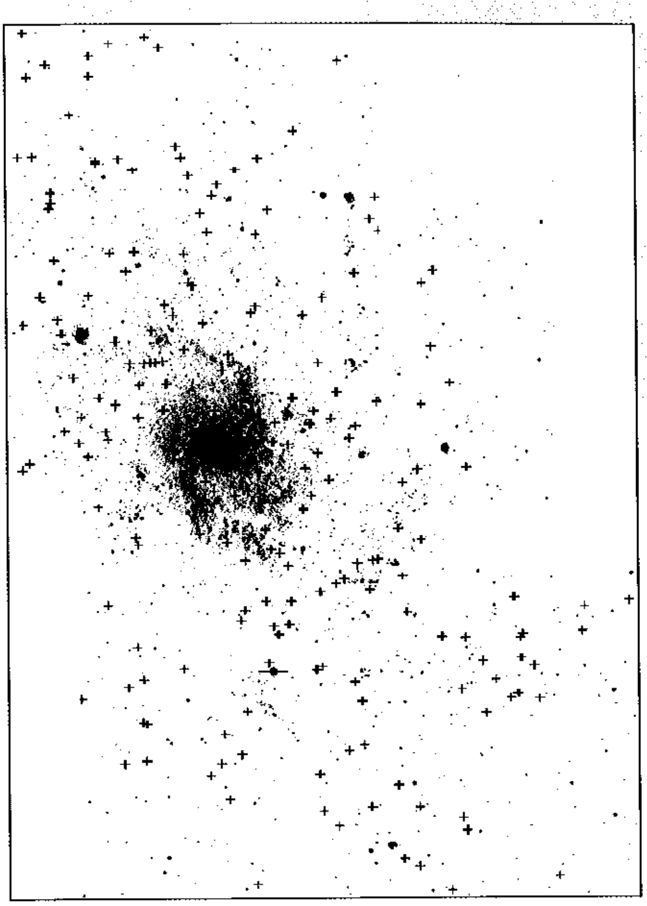
Using the planetary nebulae in nearby galaxies as templates and fitting the brightest observed planetary nebulae to this assumed cutoff, Jacoby and Ciardullo can derive distances to parent galaxies. Their distance measurements compare well with those obtained with classical methods using Cepheid variables, such as those carried out under the Hubble Space Telescope Key Project. Using 4-meter-class telescopes, astronomers have measured distances as great as that to the Virgo cluster, roughly 60 million light-years away. Because planetary nebulae exist in both spiral and elliptical galaxies, these results are less subject to biases that plague other methods.

Observations of galaxies and galaxy clusters suggest that normal matter in the form of stars and interstellar gas constitutes only a small fraction of the total mass of the universe, with the remainder in the form of dark matter. The nature of dark matter is unknown, and its existence can only be inferred from the gravitational effect it has on host galaxies and clusters. Astronomers can detect planetary nebulae far from the centers of galaxies, so they are ideal tracers of the distribution of dark matter. With their strong line emissions, astronomers can easily track the motion of planetary nebulae. Astronomers in the United Kingdom have developed a camera specifically for this purpose. In the next few years we expect to map out the distribution of dark matter in many galaxies.

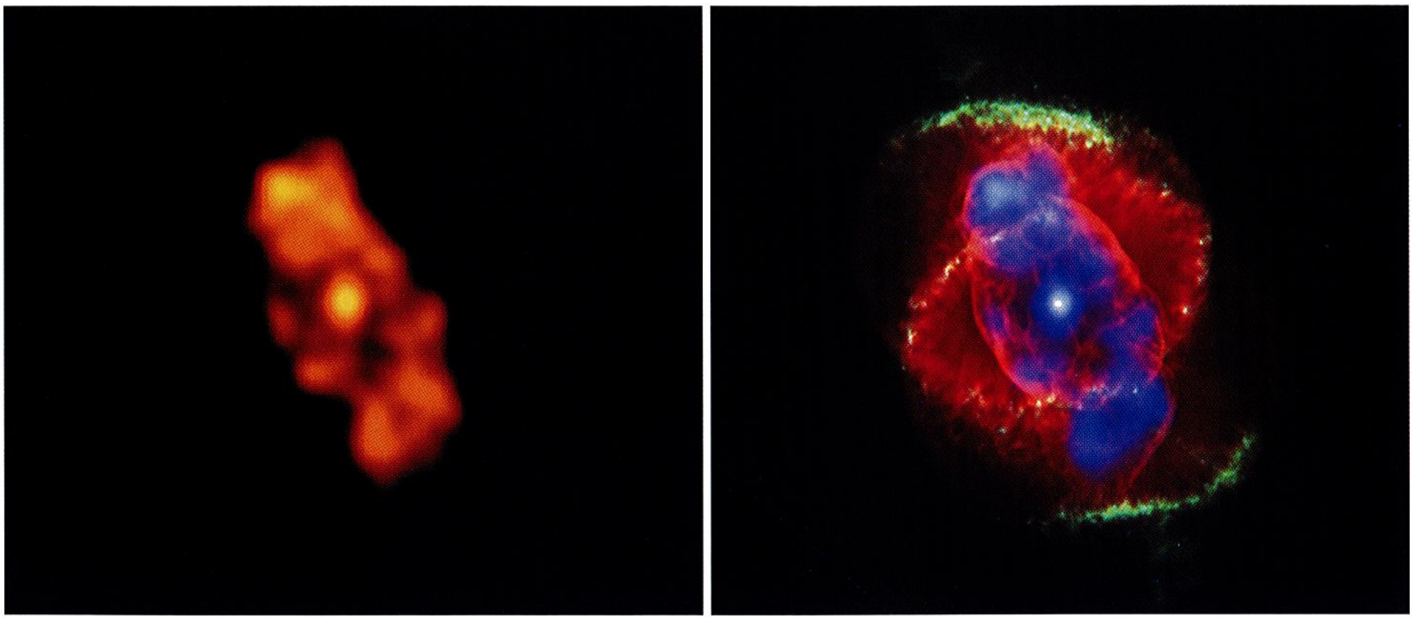
Another unexpected discovery was planetary nebulae between galaxies. Traditionally, the distribution of "normal" matter is traced by stars. But the faintness of starlight makes it difficult for astronomers to ascertain how far normal matter extends beyond the boundaries of galaxies. Because planetary nebulae radiate hundreds of times the power of the Sun in a single emission line of ionized oxygen, they are much easier to find in intergalactic space. The use of planetary nebulae as tracers of normal matter in galactic clusters began in 1996 when Magda Arnaboldi of the Osservatorio Astronomico di Capodimonte in Naples discovered three intracluster planetary nebulae in the Virgo cluster. Similar discoveries in the Fornax cluster followed.

The existence of intracluster planetary nebulae suggests that intergalactic space is not empty. John Feldmeier of Case Western Reserve University estimated that at least 20% of all stars in the Virgo and Fornax clusters lie between galaxies. Because these stars are not seen and therefore their masses are not counted, the mass of normal matter in galaxy clusters is larger than previously thought. Given that the total amount of normal matter is an important parameter in any cosmological theory, a better determination of this value could have tremendous ramifications for our understanding of the origin of the universe.

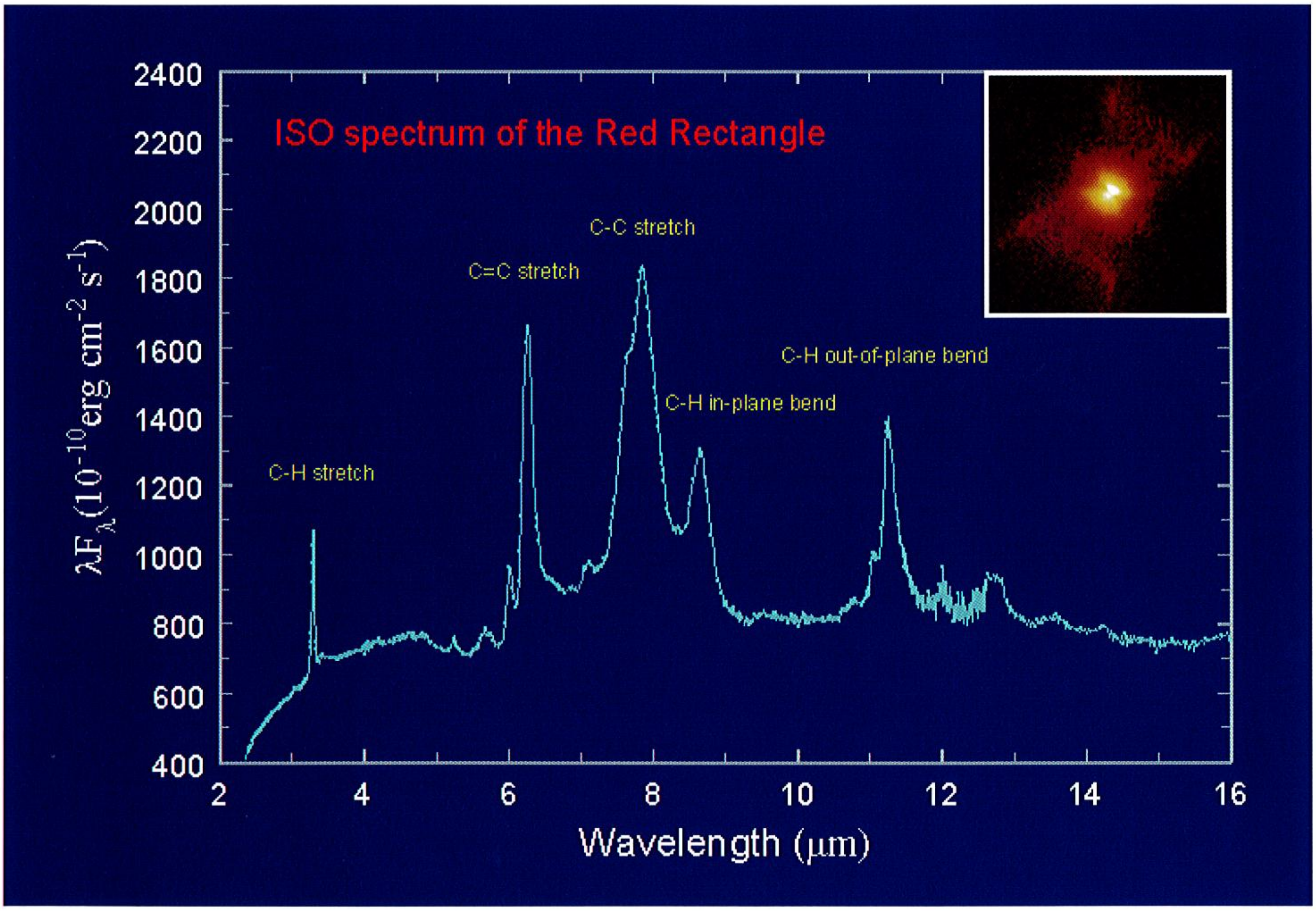
How these planetary nebulae ended up in intergalactic space is also an interesting question. When galaxies run into or pass near one another, they gravitationally interact and can tear each other apart in extreme cases (see "When Galaxies Collide," July/August 2001). Intergalactic stars are the likely results of such galactic encounters. By studying the distributions and motions of intracluster planetary nebulae, we hope to learn about the dynamical history of the cluster, including possible past galactic mergers, cluster accretions, or tidal strippings that happened long ago. — *S.K.*



**With the wide field capability available on the 2.54-meter Isaac Newton Telescope and by using a narrow-band filter centered on the 5007-angstrom, doubly ionized oxygen line, planetary nebulae can be efficiently identified in Local Group galaxies. This image shows 134 planetary nebulae (black crosses) around M33 identified by the Universitá degli Studi di Firenzi group. Courtesy of Mario Perinotto.**



**Recent observations show that planetary nebulae such as the Cat's Eye Nebula (NGC 6543) look very different depending on the observed wavelength. The image on the left shows the view of the Cat's Eye Nebula from the Chandra X-ray Observatory. Chandra reveals a cloud of multimillion-degree gas surrounding the hot central star. The composite on the right combines the Chandra image with a Hubble Space Telescope visible light image. Chandra images courtesy of NASA, You-Hua Chu (University of Illinois) et al. Hubble image courtesy of NASA/STScI.**



**The Infrared Space Observatory captures the infrared spectrum of the Red Rectangle (imaged by HST in the inset). The labeled strong features are due to radiation from an aromatic compound. HST image courtesy of Howard Bond (STScI), Robin Ciardullo (Penn State University), and NASA.**

X-rays, streams of fast-moving gas detectable only in the ultraviolet, and large chunks of solid material whose presence can only be discerned by infrared observations.

Planetary nebulae are the only celestial objects that radiate strongly throughout almost the entire electromagnetic spectrum, from the radio to X-rays. Some of the brightest radio and infrared objects in the sky are planetary nebulae. The planetary nebula NGC 7027 in Cygnus also has the distinction of having the richest optical spectrum, with many atomic elements, some down at the fifth and sixth rows of the periodic table, such as element 37 (rubidium), element 54 (xenon), and element 56 (barium). The Infrared Space Observatory detected many previously unobservable atomic lines, supplementing the optical spectrum. By determining the amount of each heavy element in planetary nebulae, astronomers can better understand how stars synthesize the various elements.

The physical conditions inside a planetary nebula can vary greatly despite the fact they are only about 500 times the size of the solar system. Temperatures can range from a low as cold as -250° C, in regions where dust and molecules reside, to a high as hot as millions of degrees Celsius in the hot bubble, where everything exists in a plasma state. The radiation environment is also extreme. There are regions that are flooded with the harshest, strongest ultraviolet light imaginable, and regions that are totally dark and completely sheltered from starlight. If we had relied on one or two instruments, we would have remained totally unaware of the complexity of these objects.

## Astromineralogy: From Rocks to Coal

Geology and astronomy used to be totally distinct scientific disciplines. After all, most of Earth's crust is made of heavy elements like iron, silicon, magnesium, calcium, and aluminum, among others. Stars and galaxies, on the other hand, are made primarily of hydrogen and helium, which Earth lost long ago because its gravity is too weak to hold onto the lightweight elements. Stars and interstellar clouds are made up of gaseous material, whereas Earth, fortunately for us, is solid. It therefore came as a big surprise when the Infrared Space Observatory discovered many common minerals, including forsterite, enstatite, diopside, and carbonates, in planetary nebulae. How planetary nebulae are able to manufacture these solid materials in a very low-density environment (almost a true vacuum) is a profound mystery.

Planetary nebulae not only produce common rocks (albeit microscopic rocks); they are also rich in organic compounds. Infrared spectroscopic studies of planetary nebulae and their immediate precursors, protoplanetary nebulae, have found evidence for a variety of organic compounds, both aromatic and aliphatic in nature. Aromatic compounds are molecules with ring-like structures; the most common everyday examples are benzene and toluene. Aliphatic chains are commonly found in fat and hydrocarbons. The structures of these materials, as far as we can determine, are not unlike that of coal, an organic substance that is the result of the decay of the remains of once living things.

Astronomers are actively investigating possible links between the production of these organic and inorganic compounds by planetary nebulae and the presence of many of these molecules in meteorites. We now know that meteorites contain traces of tiny dust grains that originated beyond the solar system. Did these grains arrive on Earth after a journey through interstellar space after they were made and ejected from planetary nebulae? It seems like a real possibility.

## More than Beautiful

Unlike galaxies, which are distant and faint, the relative brightness of planetary nebulae has allowed astronomers to take an in-depth look at their structures. Yet every time we look, either through a new spectral window, or with better angular resolution, or the high dynamic range of an optical telescope, we find new things that amaze us and cause us to question our fundamental understanding of their nature. After 200 years, research on planetary nebulae is more challenging than ever.

For astronomers who are interested in physical (and now chemical!) processes, planetary nebulae are ideal laboratories because a wide variety of physics, including nuclear, atomic, plasma, molecular, and solid-state, are at work. By studying these objects, we gain new insights into physics and chemistry that are impossible to achieve in a conventional terrestrial laboratory.

Although planetary nebulae are often called the most beautiful objects in the universe, those who work in this field have always known that they offer a lot more than sheer beauty. The next time you look at a planetary nebula through a telescope, please remember the many exciting things that are happening in these objects. **m**

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*SUN KWOK (kwok@iras.ucalgary.ca) served as chairman of the planetary nebulae working group of the International Astronomical Union between 1994 and 2001, and was the co-chairman of the scientific organizing committee of the recent IAU symposium in Canberra. He is the author of two recent books,* The Origin and Evolution of Planetary Nebulae *and* Cosmic Butterflies *(available through the ASP catalog), both published by the Cambridge University Press.*

## Image Credits

Credits for the images on page 24 (all images were taken with the Hubble Space Telescope): Menzel 3: NASA, ESA, and the Hubble Heritage Team (STScI/AURA), based on data taken by Raghvendra Sahai and Bruce Balick. Hubble 5: Bruce Balick et al. NGC 3132: NASA and the Hubble Heritage Team (STScI/AURA). IC 418: NASA and the Hubble Heritage Team (STScI/AURA), based on data taken by Raghvendra Sahai and Arsen Hajian. NGC 7662: Bruce Balick et al. NGC 7027: Howard Bond. Minkowski 2-9: Bruce Balick et al. NGC 6537: Bruce Balick et al.

All of the images on pages 26 through 28, and the ISO spectrum on page 30, were produced at the Space Astronomy Laboratory of the University of Calgary based on data from the Hubble Space Telescope archive. The original principal investigators who made the observations are: NGC 6629: Howard Bond. NGC 6826: Bruce Balick. Henize 2-47: Raghvendra Sahai. Minkowski 1-37: Raghvendra Sahai. NGC 5307: Howard Bond. Rotten Egg Nebula: Valentin Bujarrabal. Henize 3-40: Raghvendra Sahai. Cotton Candy Nebula: Sun Kwok and Matt Bobrowsky.