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NEBULA
REALLY A
RING?
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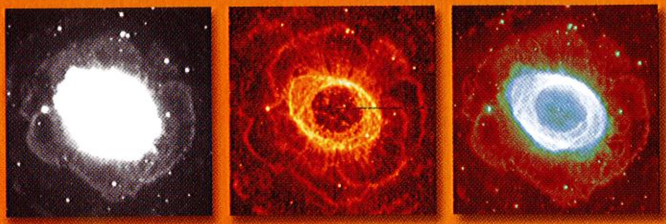


What Is the Real Shape of the Ring Nebula?

It may look like a celestial bagel, seemingly simple in design, but the structure of this planetary nebula is actually more complicated than once thought.

By Sun Kwok

The Ring Nebula in Lyra was discovered by Antoine Darquier de Pellepoix of Toulouse in 1779. He described it as "extremely faint, but perfectly outlined. It is as large as Jupiter and resembles a fading planet." Charles Messier subsequently included it as the 57th entry in his 1784 catalog of celestial objects.

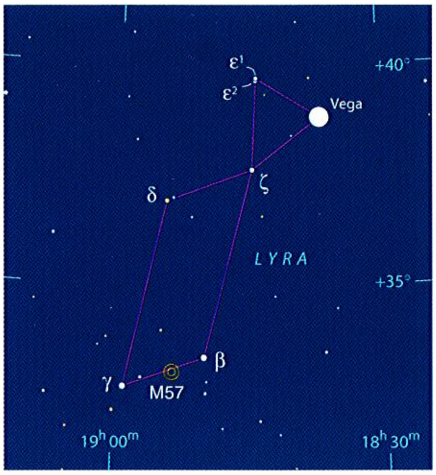
Because of its well-defined ringlike appearance, M57 is often held up as the classic example of planetary nebulae. These gaseous clouds — named in the 18th century because of their resemblance to the disk of a planet — shine by intercepting ultraviolet light from their central stars and reemitting it at visible wavelengths. As planetary nebulae go, the Ring Nebula is relatively nearby; distance estimates range from 1,000 to 2,000 light-years. The physical size of the nebula is approximately 500 times the size of our solar system.

M57 is a favorite observing target for amateur astronomers and a staple of summertime star parties. It is also among the most photographed objects in the night sky. You would think that such popularity would lead us to study M57 so well that we know everything about it. In fact, you would not be more wrong. Two centuries after its discovery, we are just beginning to understand the real story of this fascinating object.

The Ring Nebula (Messier 57) in Lyra is powered by ultraviolet light from its central star. This view of the 76-arcsecond-wide nebula was taken with the Hubble Space Telescope's Wide Field Planetary Camera 2 in October 1998. The light from helium atoms (blue) is primarily confined to the center of the ring, whereas the extent of singly ionized nitrogen (red) is much larger. Green corresponds to doubly ionized oxygen. North is to the upper right. Courtesy NASA and the Hubble Heritage Team, Space Telescope Science Institute.

A Doughnut in the Sky?

The quest to decipher the structure of the Ring Nebula began with Heber Doust Curtis, who observed many planetary nebulae with Lick Observatory's 36-inch Crossley reflector atop Mount Hamilton in California. His atlas of 78 drawings and photographs published in 1918 was the first comprehensive catalog of planetary nebulae. He classified them into various groups, using descriptive terms such as helical, annular (ringlike), disk, amorphous, and stellar. The most obvious model for the annular type is that the ring represents the projection of a hollow spherical shell on the sky — as if we're peering at a translucent balloon. The edge of the shell is brighter because we look through more glowing material along the edges compared to a line of sight through the middle.

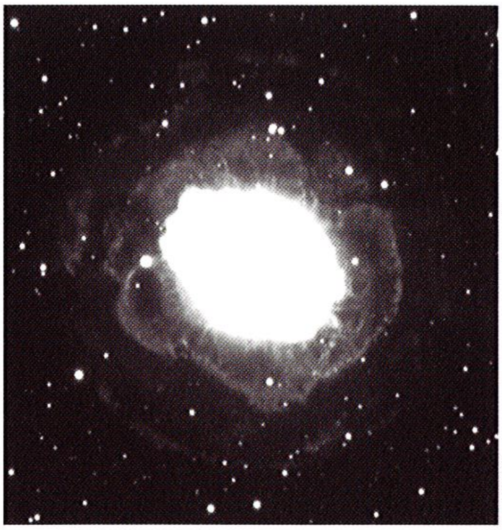


The Ring Nebula shines at magnitude 8.8 and is a favorite target for skywatchers. Its coordinates are right ascension 18^h 53.6^m, declination +33° 02′ (equinox 2000.0). While the ring shape can be viewed using small amateur telescopes, seeing the 15th-magnitude central star proves to be a challenge to observers.

Although this simple explanation is quite appealing, Curtis noticed that the surface brightness of the hole inside the ring of M57 proved insufficient. For a spherical shell, the central hole should be approximately half as bright as the ring, but instead he found the interior only 1/20 as bright. Curtis concluded that the Ring Nebula is not a spherical shell but a true two-dimensional ring lying flat on the plane of the sky.

If this is the case, and if M57 is not unique among planetary nebulae, then there should exist other ring-shaped nebulae seen at different orientations. For example, if the ring were aligned perpendicular to the plane of the sky, it probably wouldn't appear as a ring at all. Curtis suggested that M76 (NGC 650–1) in Perseus, which has a roughly rectangular shape, could in fact represent such a case. M76 looks like a nebulous bar of about 1½ by ¾ arcminutes (see the picture at the bottom of page 35). Just imagine holding a *torus* — the mathematical name for the shape of a doughnut — containing a colored liquid edge on against a light. The two ends would appear darker because light would have to pass through more material. The two ends of M76 appear brighter exactly for the same reason, except that we are dealing with a loop of gas that emits light rather than absorbs it.

This problem was picked up 40 years later by Rudolph Minkowski. He and Donald Osterbrock photographed M57 and M76 with the 200-inch telescope atop Palomar Mountain. They concluded that the two objects have the same intrinsic shape of a flattened ring. In the case of the Ring Nebula, the doughnut lies approximately 45° from the plane of the sky; for M76, the torus is seen edge on against the plane of the sky. This was viewed as a great achievement at the time, until additional observations unveiled new complications.



NOAO / NSF

A deep, 3½-arcminute-wide image of the Ring Nebula — overexposing the central portion — taken by George Jacoby at Kitt Peak National Observatory shows the faint outer halos first discovered by John C. Duncan in 1936. North is up.

Different Shapes in Different Colors

Unlike stars, which radiate in all colors, planetary nebulae shine in specific, discrete wavelengths. The ultraviolet photons emitted by the central star are absorbed by the gas, which causes the electrons to detach from the atoms — a process called *photoionization*. When these free electrons recombine with the hydrogen and helium nuclei, energy is released as photons at specific wavelengths, or spectral lines. These electrons can also collide with other atoms (oxygen and nitrogen, for example) and again create such line radiation. To make an analogy, stars are like light bulbs and planetary nebulae are similar to fluorescent tubes.

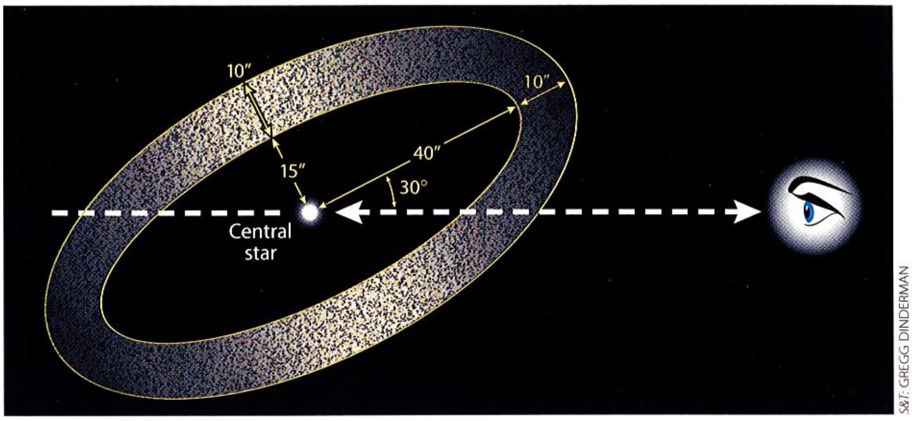
In the 1970s, Raymond Louise and Trung Hua of Marseille Observatory used the 1.9-meter telescope at Haute Provence Observatory in southern France to take images of the Ring Nebula. By using filters that allowed light from only one particular set of atoms to pass through, they found that the nebula looks quite distinct at different colors of light. They proposed that the Ring Nebula is a flattened sphere with a higher density in the equatorial regions, a compromise between the uniform spheroid and the doughnut models.

This approach was taken a step further by Newrick K. Reay and Susan Worswick (Imperial College, London), who in 1975 observed M57 with other filters using an electronographic camera mounted on the 1-m telescope at Lowell Observatory in Arizona. They found that, while in the light of neutral oxygen and singly ionized nitrogen the ring is 30 times brighter than the center, this ratio drops to only 2:1 in the light of singly ionized helium.

These studies showed that the nebula's shape varies depending on the color! It resembles a ball if we look at only the helium emission, and a torus when observed in other wavelengths. This is because of the diverse physical conditions of the gas where the emission originates. Helium atoms, requiring higher-energy photons to ionize than hydrogen or oxygen, confine their emissions close to the star. The shape of planetary nebulae is therefore not a geometric concept like a teacup or saucer (which looks the same regardless of color) but is dependent on physical processes occurring in the nebula.

The debate became heated in the mid-1970s as more players entered the ring. Paul E. Proisy (Lyon Observatory, France) suggested that M57 is a cylinder, with its major axis oriented 30° to 50° from our line of sight. L. E. Goad came to similar conclusions in his Ph.D. thesis entitled "The

Ring Nebula turned sideways? The right-hand image at the bottom of page 36 not only shows the rectangular shape that Curtis saw but also includes two faint outer lobes. Most remarkably, the axes of the bright and faint structures are off by exactly 90°! Balick suggested that unseen, high-density, neutral materials lie outside the bright core. This matter confines the central torus and forces any outflow from the star to emerge through the doughnut hole, creating so-called bipolar lobes.



By measuring the motion of the gas within M57, Colin R. Masson suggested that the nebula can be modeled as an ellipsoidal shell of uniform thickness (10 arcseconds) but having a greater density of gas along the minor axis. We see the structure at a 30° angle. The "clear" area within the shell measures 80 by 30 arcseconds. Adapted from the *Astrophysical Journal.*

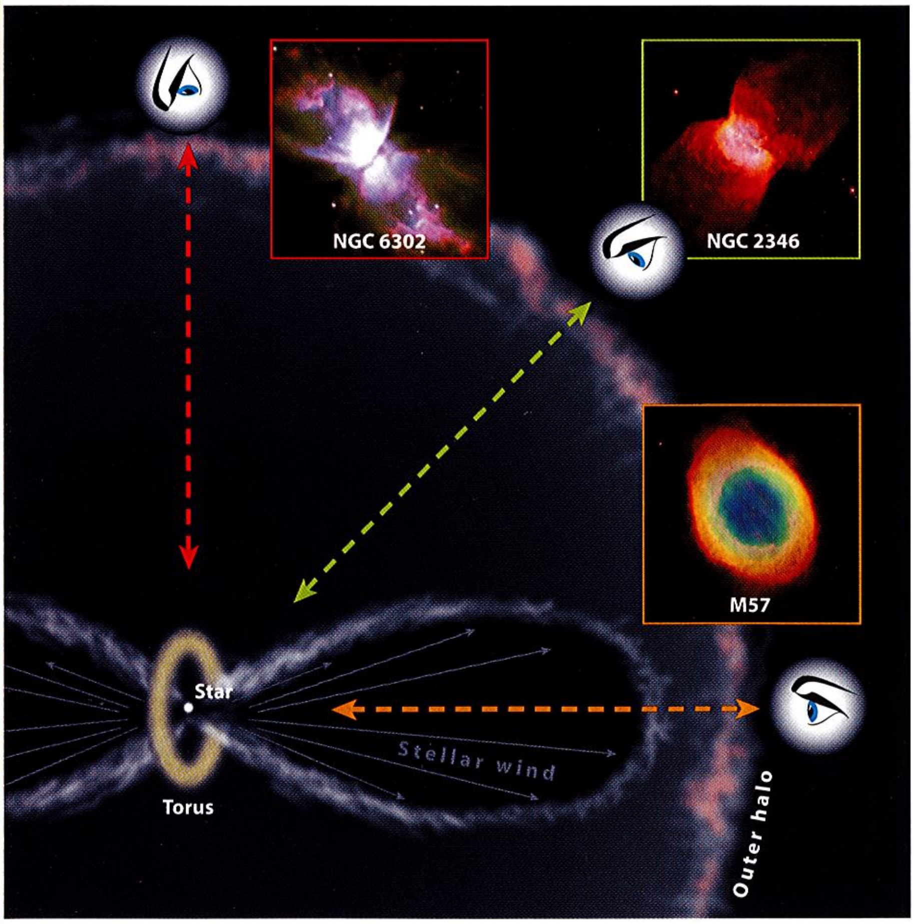
The existence of planetary nebulae with bipolar shapes has been known for a long time — NGC 2346 and NGC 6302 (see below) are good examples. Nevertheless, astronomers thought bipolar nebulae were rare, making up no more than 10 percent of the total population of planetary nebulae (most being ring or elliptical). However, the case of M76 gave us reason to be concerned. How many bipolar planetary nebulae had we missed because we had not gone deep enough? Sharpless 1–89 in Cygnus is another good example of such a case. Although it was originally classified as rectangular based on its image on photographic plates, a CCD image by Trung Hua clearly shows two bipolar lobes similar to those of M76.

So maybe bipolar planetary nebulae are more common than we thought. If that's the case, what would a bipolar nebula look like if turned sideways? Images of NGC 2346 and Sh 1–89, reveal that the ends of the lobes are larger than their bases. Thus, if we observe them along a line of sight down the major axis of the lobes, the front and back lobes will be projected onto the plane of the sky as filamentary circular blobs, not unlike the halos that we see in the Ring Nebula! It is therefore not inconceivable that M57 is in fact a bipolar nebula.

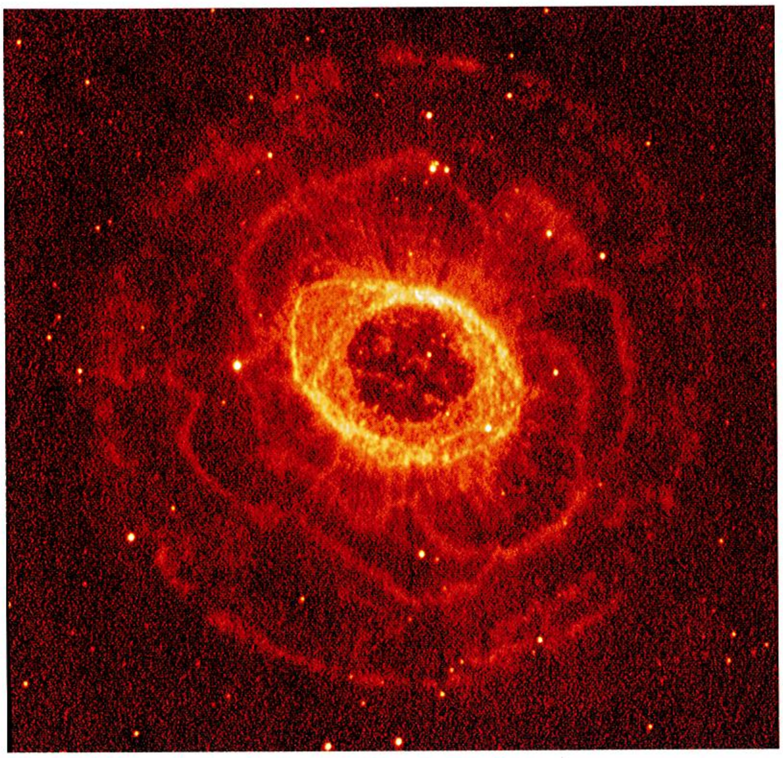
This is precisely the conclusion arrived at in 1994 by Myfanwy Bryce (University of Manchester), Balick, and John Meaburn (then at Leiden University). By taking spectra of the Ring Nebula at several spots and measuring the Doppler shift — changes in the wavelength of light because the source is approaching or receding — they were able to show that the inner halo can be explained by expanding front and back lobes. The outer halo is the remnant of the envelope ejected when the star was a red giant.

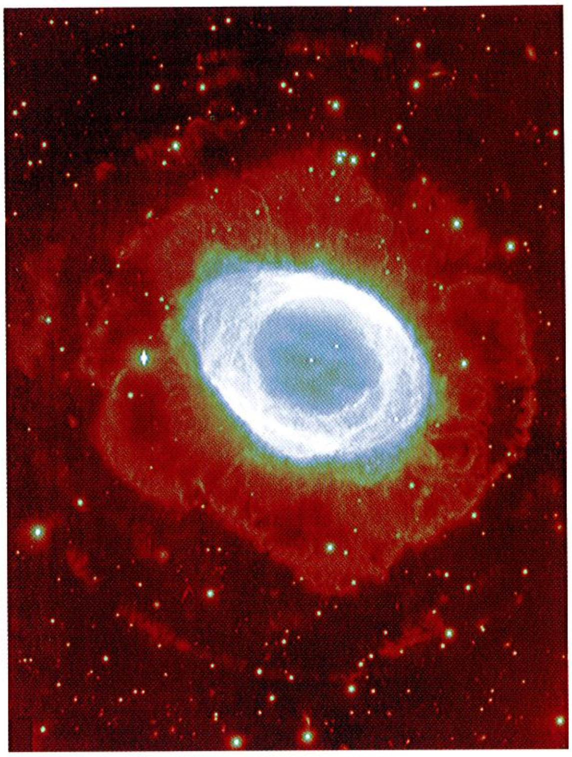
A Universal Model

Astronomers have long been puzzled by the variety of shapes seen in planetary nebulae. It is tempting to believe that such diversity is just different manifestations of one basic three-dimensional structure. The first attempt to characterize such a form was made by the Russian astronomer Gabriel Khromov and the Czech researcher Lubos Kohoutek (*S&T:* October 1969, page 227). They emphasized the effect of viewing angle on the apparent structure of planetary nebulae and suggested in 1968 that



Today many astronomers believe that the various forms seen in planetary nebulae can be explained by one model that we see from different angles. Flows of gas from the central star are funneled out perpendicular to a denser torus of material girdling the star. If we sight down the axis of the flow, we see a round nebula like the Ring. Looking from "above," the bipolar flows are conspicuous, as with NGC 6302. Peering at an in-between angle produces an image much like that of NGC 2346 in Monoceros.





Left: **Spikelike streams of outflowing gas and dual halos can be seen in this false-color infrared image of the Ring Nebula taken at Calar Alto Observatory in Spain. The filter was centered around the 2.12-micron emission line of molecular hydrogen. Courtesy National Astronomical Observatory of Spain.** ***Right:*** **A false-color hydrogen-alpha image of M57 taken on May 14, 1999, with the 8.3-meter Subaru Telescope atop Mauna Kea also shows the halos. The inner oval-shaped halo what we see down the bipolar flows of gas, whereas the much fainter outer circular halo is the remnant of the slow wind cast off from the central star when it was a red giant. Courtesy National Astronomical Observatory of Japan.**

many of the observed shapes can be explained by cylinders with open ends viewed at different orientations on the sky.

Another attempt to create a universal model of planetary nebulae was made in 1990 by Colin R. Masson (then at Harvard-Smithsonian Center for Astrophysics). He proposed that the structure of the Ring Nebula is consistent with a spherical shell that varied in density both radially and latitudinally (see top diagram on opposite page). Since the central star has only a finite output of ultraviolet photons, the nebula is ionized to different depths along various directions. When projected upon the plane of the sky, the ionized shell can have shapes ranging from rings to hourglasses, depending on the viewer's perspective.

Although the Masson model — now commonly referred to as the ellipsoidal-shell (ES) model — has more parameters than the previous scenarios, its advantage lies with the introduction of physics (photoionization) into the problem. The power of the ES model was illustrated by Orla Aaquist and me when we fitted many radio images of planetary nebulae with the model. In 1998 I worked with Cheng-yue Zhang in a more ambitious effort to fit 110 planetary nebulae.

Given the fact that Khromov and Kohoutek did not have the benefits of today's CCD imagery, their idea was remarkably insightful. We now believe that the brightest part of the nebula has the shape of a short cylinder (a tall torus), but the polar extensions are fan shaped. The finite extent of the cylinder is determined by ionization effects. The lobes, however, are created by a combination of dynamical and ionization effects.

A schematic picture of a universal model of planetary nebulae is shown on the opposite page. The torus, having higher densities, forces the outflow from the star to channel through the open ends. After breaking out, the outflow fans out to the side, giving the planetary a butterfly shape. Looking down the symmetry axis, the nebula looks like a ring with faint halos, exactly like the Ring Nebula.

The idea that the lobes represent the breakout of a fast outflow from an existing cocoon is supported by the observations of protoplanetary nebulae (*S&T:* October 1998, page 30). When this outrushing gas runs into the remnant of the star's red-giant wind, it creates shock fronts. The signature of shocks can be found by an emission line of molecular hydrogen (H_2) at the wavelength of 2.12 microns. Viewing M57 at this infrared wavelength (see the left-hand image above) reveals streams and filaments that could be evidence of shock interactions.

Do we finally have the truth about the nature of M57? It is difficult to say, but surely we have learned some very valuable lessons. The goal of science is to reduce the apparent chaos and complexity of nature to basic principles. We have accumulated a lot of evidence that celestial rings and butterflies are the same thing. It would be truly amazing if all the animals in the planetary-nebula zoo could be explained by this simple model. This story has also taught us humility: even such a well-studied and seemingly self-evident object as the Ring Nebula can keep its real nature hidden for more than 200 years.

University of Calgary astronomer Sun Kwok *(kwok@iras.ucalgary.ca) is chairman of the Working Group on Planetary Nebulae of the International Astronomical Union. His new book,* The Origin and Evolution of Planetary Nebulae, *is available from Cambridge University Press.*