MORPHOLOGY OF PLANETARY NEBULAE

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When we look at planetary nebulae, we are by definition looking at similar objects and yet, the pictures which we exhibit show many dissimilar features. In fact, individual planetary nebulae have names that are associated with their peculiar features. There are, for example, the Helix, the Dumbbell, the Ring and the Eskimo.

Not only can different nebulae have different forms but the same nebula can have different forms depending on the wavelength region in which it is observed. NGC 7293 (the Helix) is a case in point. The most familiar photographs of this object are those obtained by Baade and Minkowski in the 1950's such as the one shown in Figure 1. This photograph was taken in red light and the image is due to combined Hα and [NII] emission.

The red image of NGC 7293 is quite faint at small angular distances from the central star. However, when the red light is dispersed into separate components and photographed in Hα and then in [NII], two qualitatively different images result. Figure 2 is the [NII] photograph obtained by Carranza et al. (1968). The [NII] image is similar to the photograph in Figure 1 in that it is very faint at small angular distances from the central star. On the other hand, the Hα image obtained by Carranza et al. (Figure 3) is much more uniform across the disc and there is obvious emission in regions with small angular distances from the central star.

One interpretation is that the regions physically close to the central star are devoid of material and the emission seen at small angular distances from the central star comes from peripheral material. Khromov and Kohoutek (1968) have constructed a classification scheme based on Khromov's (1962) suggestion that each planetary nebula consists of faint peripheral material enveloping a hollow "main structure" which is common to all planetary nebulae. The "main structure" is assumed to be a toroid. Shelled objects such as the Ring Nebula and butterfly structures such as the Dumbbell Nebula are represented as different orientations of the toroid,

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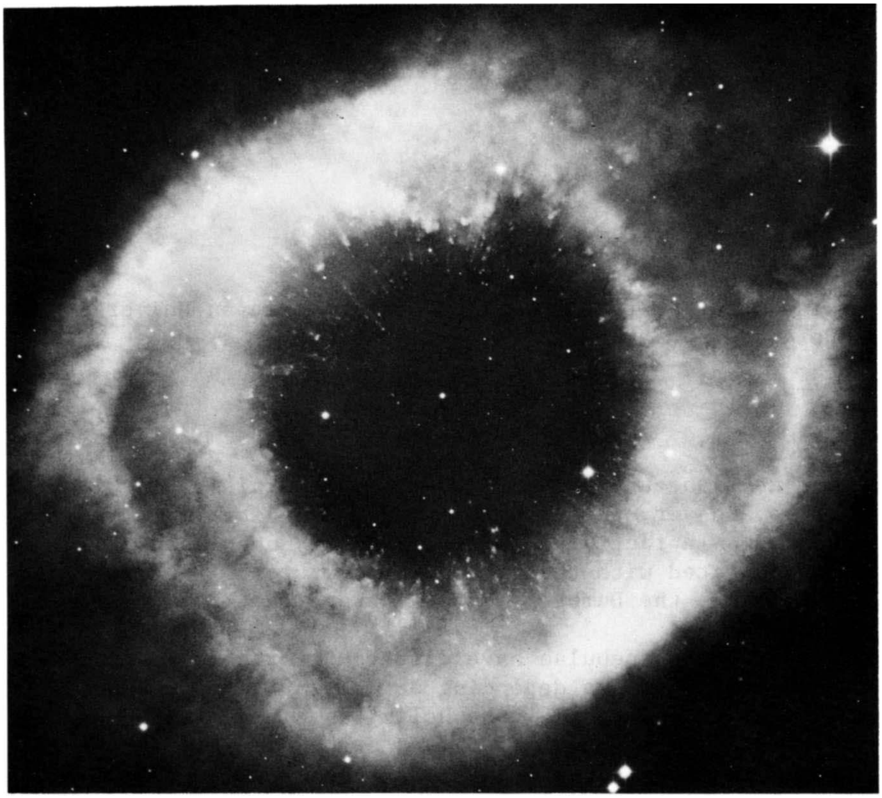

Figure 1. NGC 7293 - The Helix Nebula
(Hale Observatories Photograph in Hα and [NII])

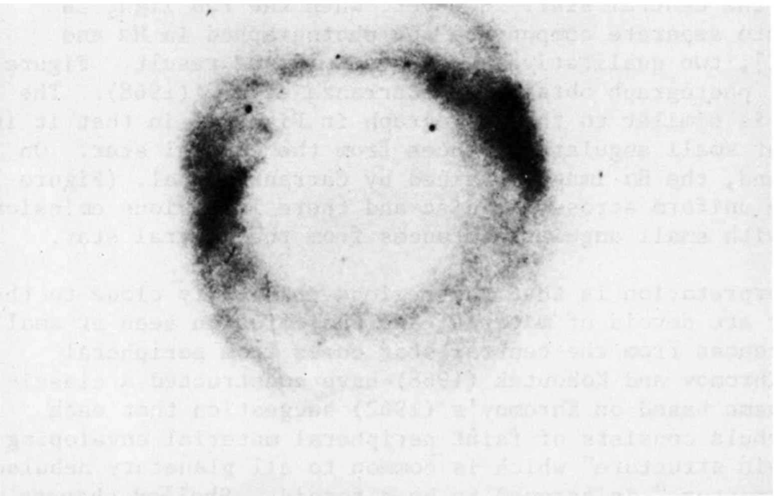

Figure 2. NGC 7293 in [NII].

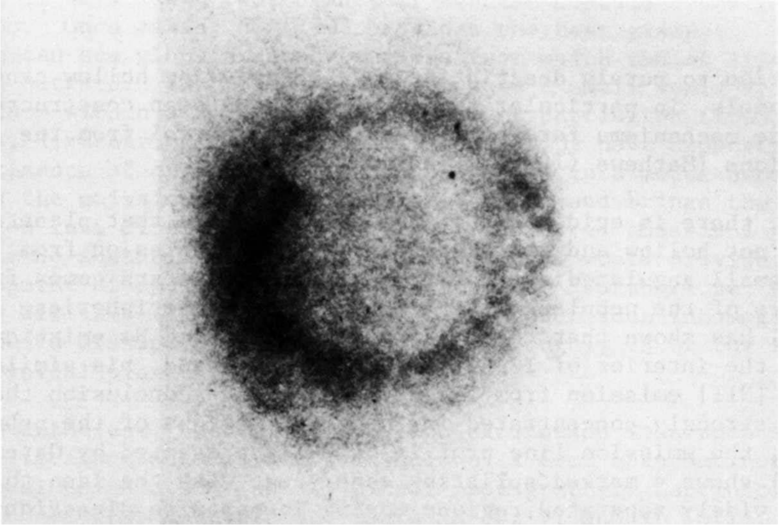

Figure 3. NGC 7293 in Hα.

Figure 4. NGC 2392 - The Eskimo Nebula.
(Lick Observatory Photograph).

along with slight differences in the distribution of peripheral material.

In addition to purely descriptive models employing hollow centers, dynamical models, in particular for NGC 7293, have been constructed which include mechanisms for the evacuation of material from the central regions [Mathews (1966), Pikelner (1973)].

However, there is evidence that supports the idea that planetary nebulae are not hollow and at least part of the HI emission from regions at small angular distances from the central stars comes from the interiors of the nebulae rather than from their peripheries. Aller (1956) has shown that there is relatively strong Hα emission coming from the interior of IC 418. On the other hand, his similar analysis of [NII] emission from IC 418 leads to the conclusion that N^+ ions are strongly concentrated in the outer regions of the nebula. In addition, the emission line profile of [NII] presented by Osterbrock (1968) shows a marked splitting consistent with the idea that N^+ inhabits widely separated regions moving in opposite directions along the line of sight. However, the HI emission line profile obtained by Osterbrock for IC 418 has a single hump indicating that a sizeable fraction of the HI emission comes from more slowly expanding material located in the interior of the nebula.

The difference between the H^+ and N^+ distributions is qualitatively consistent with the idea of ionization stratification in planetary nebulae. The degree of ionization is expected to decrease with increasing distance from the central star as a result of the attenuation of the stellar radiation. Close to the central star, nitrogen is expected to be in doubly ionized and even triply ionized form and only in the outer regions is singly ionized nitrogen expected. On the other hand, wherever there is visible nebular gas there is ionized hydrogen.

The idea of ionization stratification can also be applied to oxygen. In order of increasing distance from the central star, one expects successive zones of maybe three times ionized oxygen, certainly doubly ionized oxygen, then singly ionized oxygen and, in radiation bounded nebulae, neutral oxygen.

There is no question that there is qualitative agreement between the theory of ionization stratification and observation. As early as 1950, the classical study of motions and image sizes by Wilson verified that the overall excitation in a nebula decreases with increasing distance from the central star. However, quantitatively, the emission predicted by model calculations for the lower excitation ions such as $[N^+]$, $[O^o]$ and $[O^+]$ is always lower than the observed emission when the ionization structure is assumed to be a simple shell-like stratification.

It is well known that planetary nebulae contain density condensations. Once again, NGC 7293 provides the best example. In Figure 1, one can see globular condensations from which radial filaments extend outward. Inhomogeneities can cause a small scale ionization structure within a given stratum. In fact Harrington (1969), Flower (1969), Kirkpatrick (1970) and Williams (1970) have demonstrated that the presence of optically thin condensations in a model nebula enhances the emission by lower excitation ions and brings the predicted emission into closer agreement with the observed emission. However, to date no instabilities have been found that would provide for the development of optically thin condensations. Furthermore, as pointed out by Williams (1970), given the existence of such inhomogeneities, they would dissipate in about 100 years, roughly 1% of the lifetime of a typical planetary nebula.

Nevertheless, the emission by low excitation ions such as N^+, O^o and O^+ is associated with condensations, a fact born out not only by the model calculations but by direct photography. Capriotti et al. (1971) photographed the Ring Nebula in [OIII] and in [OII]. The [OIII] image is much more uniform than the [OI] image. The same authors photographed the Dumbbell Nebula in Hβ and in [OI]. The Hβ image of the Dumbbell is quite uniform while the [OI] image shows conclusively that [OI] emission is restricted to particular locations in the nebula and does not originate throughout a particular stratum.

In their study of the small scale structure of the planetary nebulae, Capriotti et al. show that, unlike optically thin condensations, optically thick condensations as small as 10^{15} cm in diameter could survive for the lifetime of a planetary nebula. It was concluded in this work that the small scale ionization structure is associated with optically thick condensations.

In 1972, Van Blerkom and Arny demonstrated that optically thick condensations could create the appearance of NGC 7293 when photographed in NII emission. The filaments extending radially outward from the condensations are considered to be shadows, that is, regions shielded against ionizing radiation from the central star. Only diffuse radiation resulting from recombination of protons and other ions with electrons in the nebular gas can reach the shadowed regions. Since the diffuse radiation corresponds to a relatively low temperature of about 10^4 K, the shadowed regions are expected to contain low excitation ions, while the unshadowed regions should contain higher excitation ions. Consequently, not only is the small scale ionization structure understandable when explained in terms of optically thick condensations and their associated filaments (shadows), but so is the hollow appearance of NGC 7293 and other planetary nebulae when they are observed in emission from low excitation ions. This emission is expected to come only from regions beyond the condensations. On the other hand, HI emission is expected from all parts of the nebula that are ionized, including the interior of the nebula.

The condensations do not seem to be uniformily distributed throughout a nebula, but rather, they seem to be confined to a narrow zone and as a result of this distribution divide a nebula into two parts, the inner part having a more or less stratified ionized structure and the outer part a smaller scale, localized ionization structure. Figure 1 shows that the condensations in NGC 7293 lie in a relatively narrow zone a bit more than half way from the central star to the outer edge of the nebula.

Capriotti (1973) has shown that the ionization front in a young, radiation bounded planetary nebula can suffer a Rayleigh-Taylor type instability when the nebula reaches a certain size. The neutral hydrogen shell outside the ionization front would fragment as a result of this instability, and the formation of optically thick condensations with diameters of the order of 10^{15} cm is predicted.

If the condensations do in fact form as the result of the fragmentation of the neutral hydrogen shell in a young planetary nebula, one expects to find them only in a rather narrow zone lying not too far from the outer edge of the nebula as is observed for NGC 7293. Furthermore, the angular size of a typical condensation in NGC 7293 is no larger than 1", and if one takes the distance of this object to be 137 ps. (O'Dell 1962), then the typical condensation is no larger than 1.7 x 10^{15} cm, close to the size predicted by Capriotti (1973).

Assuming that optically thick condensations do exist, one is led to wonder if they have any connection with the presence of dust in planetary nebulae. The presence of dust has been inferred from the infrared emission observed in planetary nebulae first by Gillett et al. (1967), and since then by several others. The infrared study of NGC 7077 by Becklin and Neugebauer (1973) is of particular interest. Their right ascension scans through the center of NGC 7027 at 20, 10 and 2.2 microns show that emission is definitely confined to widely separated regions on opposite sides of the center of the nebula. Perhaps there are optically thick condensations in NGC 7027 arranged similarly to those in NGC 7293. Then low excitation zones associated with the condensations and the interiors of the condensations themselves might provide hospitable environments for dust particles. In any case, the infrared measurements of NGC 7027 by Becklin and Neugebauer show conclusively that dust is present within the confines of the ionized nebular gas because the infrared image is about the same size as the optical image. Furthermore, infrared studies of NGC 6537, IC 418, BD +30°3639 and NGC 6572 by MacGregor et al. (1976) show that in each case the 10 micron image is smaller than the HI image. In these objects as well as in NGC 7027, the dust is imbedded in the gas suggesting that the dust and nebular gas have a common origin, material ejected from the central star.

The infrared contour map of NGC 7027 constructed by Becklin and Neugebauer has the same general form as the radio contour map constructed by Scott (1973). There is a bipolar intensity distribution in each case. However, the radio image is much more amorphous than the infrared image and does not have an extreme central depression. Similar bipolar distributions have been obtained by Terzian et al. (1974) in their radio synthesis observations of several planetary nebulae. Since the radio contours are essentially maps of the hydrogen distribution, it is of interest to compare them to HI optical emission line maps.

Coleman et al. (1975) have obtained Hβ isophotes for several planetary nebulae. In general there is good agreement between the Hβ and radio contour maps. In both cases, the images are rather amorphous, but with only a hint of bipolar structure in the Hβ maps and definite bipolar structure in many of the radio maps.

As mentioned before, the true distribution of material is not obvious in the photographs most commonly exhibited because of ionization effects. In fact, one might say that these photographs are selected in a biased fashion to show vivid, detailed structure. One can conclude that the radio maps and the Hβ maps give the better picture of the general distribution of material in the planetary nebulae while the photographs featuring ionic emission give the better picture of the distribution of inhomogeneities.

In any case, the radio maps, Hβ maps, and the photographs all show that usually the distribution of the material in a planetary nebula is not the same in all directions from its central star. However, objects with completely different appearances such as the Ring Nebula and the Dumbbell Nebula do have common symmetries. They are each rather symmetrical around a pair of perpendicular axes, one of which is almost always longer than the other. It has been suggested that the axial symmetry of the planetary nebulae results from their ejections from stars with axial symmetry, perhaps due to rotation. Kirkpatrick (1976) has shown that the envelope ejected from a star with just a few percent oblateness will have as much as sixty percent oblateness by the time it reaches a size comparable to that of a planetary nebula.

However, there is remarkable evidence that the shapes of planetary nebulae may be completely unrelated to axial symmetries of their parent stars. To be specific, Grinin and Zvereva (1968) and later Melnick and Harwit (1976) have shown that there is a tendency for the long axes of planetary nebulae to be aligned with the plane of the galaxy. If this is true, then it is more likely that the shapes of planetary nebulae are due to some property of the galaxy rather than to some property of their parent stars. As a matter of fact, Gershburg (1968) pointed out that the galactic magnetic field might impede the expansion of a planetary nebula in directions perpendicular to the galactic plane, and lead to an elongation of the nebula in the galactic plane. However, the gas pressure in a planetary nebula is several orders of magnitude greater than the average pressure of the galactic magnetic field. Therefore, any noticeable effect on the expansion of a nebula by the galactic magnetic field would have to result from the field's compression by the expanding nebula. It is interesting to note that if the galactic magnetic field does indeed influence the expansions of the planetary nebulae, then their forms should be prolate rather than oblate.

Finally, I should like to discuss an often overlooked property of the planetary nebulae; the existence in many cases of one or more fainter shells surrounding the main nebula. These shells have thicknesses ranging in size between one-half and three times the radius of the main nebula. O'Dell (1962) distinguished between thin shells closely related to the main nebula such as the shells around the Ring Nebula and NGC 650 which were observed by Minkowski and Osterbrock (1960) and the somewhat larger, detached shells such as that of the Eskimo Nebula (Figure 4) which probably results from a double ejection of the central star.

Wentzel (1976) has considered the various ways in which the outer shell might evolve if double ejection would occur. He concludes that one of three things would happen:

1) The first nebula expands, ionizes and then recombines when a second nebula is ejected. Later, when the second nebula becomes optically thin, the first nebula becomes ionized again and appears, by comparison to the second nebula, as a faint outer shell because of its lower density.

2) The first planetary expands and never ionizes until the second planetary becomes optically thin. As a result, an unstable ionization front moves through the first nebula and it fragments into globules. Again two distinct objects result, but in this case the faint outer shell is inhomogeneous.

3) The expansion of the first nebula is impeded by the interstellar gas allowing the second nebula to catch up. The first nebula is compressed by the second nebula and when the first nebula ionizes it resembles the thin shells surrounding the Ring Nebula and NGC 650. Consequently, in Wentzel's description, the thin shells also are to be considered as earlier ejecta of the central stars.

In addition to the planetary nebulae which possess the outer shells described above, there are several which possess giant halos [Duncan (1937), Kaler (1974), Millikan (1974)], whose radii are greater than five times the radii of their respective main nebulae. Figure 5 is Millikan's photograph of the halo around NGC 6826. The angular radius of the halo is about 70" while that of the main nebula is only about 13".

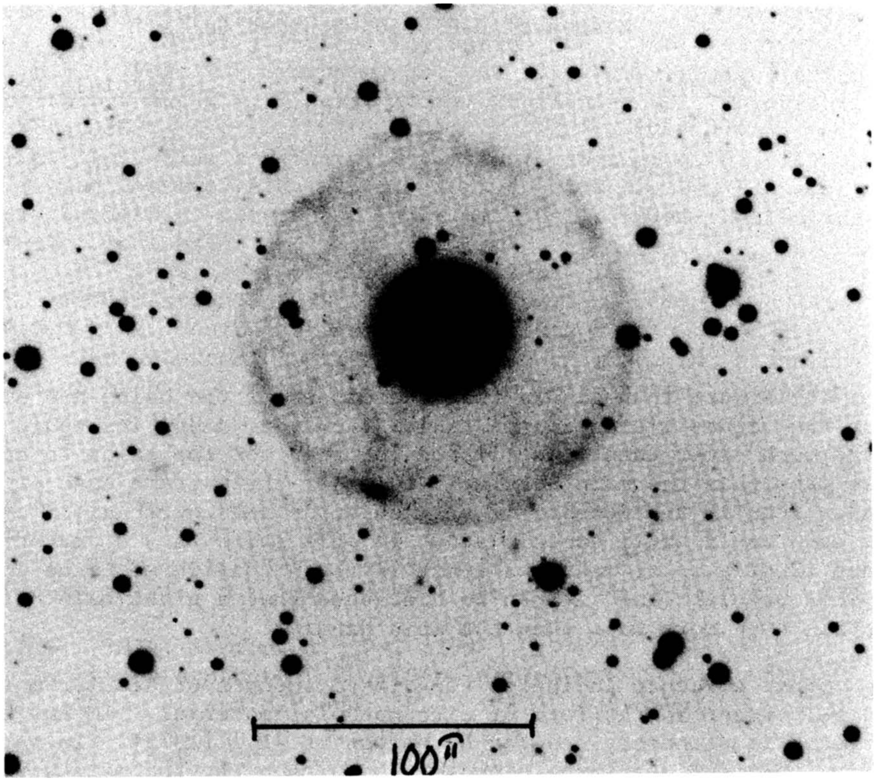

Figure 5. NGC 6826
(KPNO 4-m telescope photograph).

Kaler (1974) argued that the halos are probably not due to illumination of the general interstellar medium since some of the planetary nebulae with giant halos lie at fairly great distances from the galactic plane. Also, according to Czyzak et al. (1968), the bright knot in the halo of NGC 6543 has a density of 500 cm^{-3}, quite a bit higher than the general density of the interstellar medium. It is more probable that the halos are either planetary nebulae ejected earlier by the parent stars or they are material lost in stellar winds prior to the ejection of the nebula by their parent stars.

Since the halos are so large, they could have very low densities and still contain very large masses of material. A halo cannot be more massive than the Strömgren sphere with the same radius. The masses of the Strömgren spheres corresponding to the halos of several planetary nebulae are listed in the table. The angular radii and distances used to estimate these masses were taken from Millikan (1974) and Seaton (1966) respectively. The Strömgren masses listed in the table are considerably larger than the masses assigned to the progenitors of the planetary nebulae.

Masses of Radiation Bounded Halos

Object	Halo Mass	Particle Density
NGC 6309	10 $M_\odot$	230 cm^{-3}
6543	24	130
6804	2	1500
6826	8	360
6853	5	600

It is more than likely that the masses of the halos are smaller than the values listed in the table. However, densities would have to be much lower than those listed in order for the halos to contain less mass than the main nebulae. Consider the extreme case of NGC 6543. Even if the density of this object's halo were only 1 cm^{-3}, the halo would still contain about 12 of a solar mass of material. Since .2 of a solar mass has generally been considered to be the typical nebular mass, it can be concluded that a giant halo may contain even more mass than the main nebulae.

Other evidence indicates that large amounts of nebular material may be present in the form of circumnebular material. CO has been detected in planetary nebulae by Mufson et al. (1975). In particular, they found a large cloud of CO surrounding the main structure of NGC 7027. The cloud's linear dimensions are about five times greater than those of the nebula itself. The mass of this cloud has been estimated to be about 1.4 M_O, again a number much greater than that usually expected for a planetary nebula. The existence of giant halos and molecular clouds surrounding the planetary nebulae may make it necessary for us to revise our ideas regarding the nature of their parent stars and the manner in which they evolve.

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