Session IV

STRUCTURE AND DYNAMICS

MORPHOLOGICAL STUDY OF PLANETARY NEBULAE

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There are two approaches to the problem of the dynamics of planetary nebulae. The first is based on the investigation of the velocity fields in the nebulae. The second can be carried out by studying the spatial distribution of the matter in these objects. In an ideal case both approaches can be united. However, data on the velocity fields in planetary nebulae still are very scarce and fragmentary and their rate of accumulation is rather slow.

At the same time, there is sufficient observational basis for a morphological study of planetary nebulae. That is why the second approach has been chosen by the authors of the present paper; the morphology of planetary nebulae will be studied for the purposes of constructing spatial models of them, and of investigating the general character of the velocity fields in these objects.

In the first section of the present paper methods and results of analysis of the observational material will be presented. In the second part the data from the previous section will be used to derive a spatial model and to outline a dynamic picture.

1. A morphological study of objects of a given class should be started by developing an empirical classification of their observed forms. The variety of observed forms of planetary nebulae makes this first task rather difficult, and observational problems complicate it still more.

Probably for these reasons some earlier classification systems were entirely descriptive, contained no attempts at generalization and lacked a clear physical background. As a result the opinion was established that planetary nebulae are a collection of objects with a wide variety of different spatial structures.

We believe that this idea has no reasonable physical basis. It should be kept in mind that planetaries constitute a group of related objects united by a common genesis. It seems questionable that one mechanism which is responsible for the origin of planetary nebulae could create many entirely different spatial structures, or even a set of several different types of them. That is why in our morphological study primary attention has been paid to searching for common features inherent in all planetary nebulae.

The observational basis for the present study was provided by a collection of original

Osterbrock and O'Dell (eds.), Planetary Nebulae, 227–235. © *I.A.U.*

photographs and reproductions of planetary nebulae, which were collected by Perek and Kohoutek at the Astronomical Institute of the Czechoslovak Academy of Sciences in Prague. Originally this material was used in the preparation of the *Catalogue of Galactic Planetary Nebulae* (1967).

The total number of known planetaries is 1036; 295 objects were finally selected for the morphological study. The overwhelming majority of the others were stellar planetary nebulae and could not be studied from a morphological point of view. Some 80 objects showed overexposed images and could not be studied for this reason.

A basic principle of our classification of observed forms of planetary nebulae was the same as it was formulated by one of the authors some years ago (Khromov, 1962). This principle states that in each planetary nebula one can distinguish a bright and compact 'main structure' which is submerged into a fainter and elongated 'peripheral structure'. The average ratio between the surface brightnesses of the main and peripheral structures is about a factor of 10, which corresponds to at least a factor of 3 in density. It appears therefore that the main structure contains the largest portion of the observable mass of a planetary nebula.

The study of the observed forms of a large number of planetaries showed that there exist three types of observed forms of the main structure. These types – we have marked them by numerals 1, 2, and 3 – are clearly distinguishable and differ from one another by their degree of deviation from a regular ring-shaped form.

The peripheral structures are much more individual, but nevertheless one can trace certain common features. We were able to subdivide all observed forms of peripheral structures into three types – a, b, and d. Moreover, a set of simple geometrical characteristics of the main and peripheral structures was defined for further quantitative analysis.

The classification types of the main and peripheral structures can be seen in Figure 1, where all the principal cases are presented.

Table 1 shows the distribution of nebulae studied according to the types of their main and peripheral structures.

Table 1

Type of the nebula	1		2				3				
Characteristic of peripheral structure	–	d	–	a	b	d	–	a	b	ab	ad
Number of objects classified	66	14	49	27	2	6	26	34	25	11	3
Total number	80		84				99				

The total number of objects classified was 263, which is about 90% of the nebulae studied. Each nebula was classified by both of the authors of this paper independently. The cases of disagreement were rather rare. Peculiar objects which could not be properly classified within the limits of our scheme were mostly faint with no trace of regular structure.

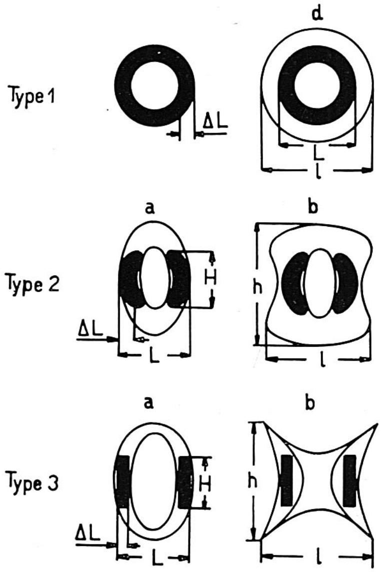

FIG. 1. *Schematic drawings of three classification types, with significant dimensions indicated.*

2. In the second part of our paper we shall consider the question of the spatial structure of planetary nebulae. Many authors have studied this problem, and among the papers which have been written on this subject one should particularly mention the classical study of Curtis (1918), containing many ideas developed later by others. Both Curtis' paper and the later papers are mostly devoted to individual cases and contain no attempts at generalisation of the results.

One of the most important studies in our opinion is the paper by Minkowski and Osterbrock (1960), in which two planetary nebulae – NGC 6720 and NGC 650-1 – were considered. In this paper it was definitely stated that many planetaries, in spite of their apparent forms, could have a toroidal structure.

Some years ago one of the authors of this report (Khromov, 1962) suggested that all observed forms of planetary nebulae can be explained by projecting upon the sky one common spatial structure. In the present paper an attempt is made to revise this old idea on the basis of more complete observational material.

The supposition that effects of projection can play a primary role in determining the observed structures of planetary nebulae forces us to review the question of the spatial orientation of the nebulae. We investigated the distribution of angles between the apparent axes of planetary nebulae and the galactic equator. The axis of a nebula of type 2 or type 3 was determined as the perpendicular to a line connecting the two maxima of brightness. The results of this study, which included 182 objects, definitely prove a random orientation of planetary nebulae.

Now we can analyse the morphological data provided by our classification. It is reasonable to begin by considering the main structure.

Remembering the three types of observed forms of the main structure of planetary nebulae, one can easily realize that such an empirical picture can be explained by the supposition that the main structure of the nebulae actually is a toroid. If this toroid

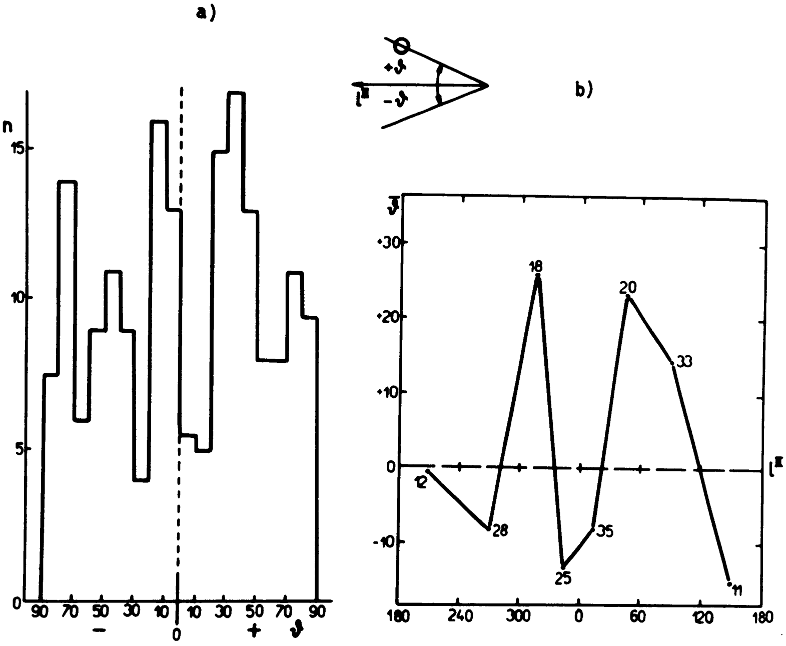

FIG. 2. *(a) Histogram of angle between axes of planetary nebulae and galactic equator. (b) Mean angles between axes and galactic equator as a function of galactic longitude. The figures at the points of the graph indicate numbers of objects contributing at a given point.*

is seen from the direction of its axis of rotation, we see a ring-shaped type-1 structure; looking at it from its equatorial plane we see a type-3 structure. Finally, the structures of type 2 correspond to an intermediate case of projection.

For simplicity we consider this toroid a right-angled one; its average geometric parameters can be determined from the observed classification data. The corresponding histograms show that the average value of the parameter $\Delta L/L = 0{\cdot}24$ is determined quite reliably by 211 objects. The second parameter, H/L, shows a considerable scatter, but an average estimate 0·65, determined by 183 objects, is reliable enough.

The mean spatial parameters of the main structure can be used to compute corresponding isophotal pictures that one would observe looking at such a structure at different angles between the line of sight and the axis of the toroid. It can be shown that this picture has a good qualitative agreement with the real one observed in the light of H and He lines.

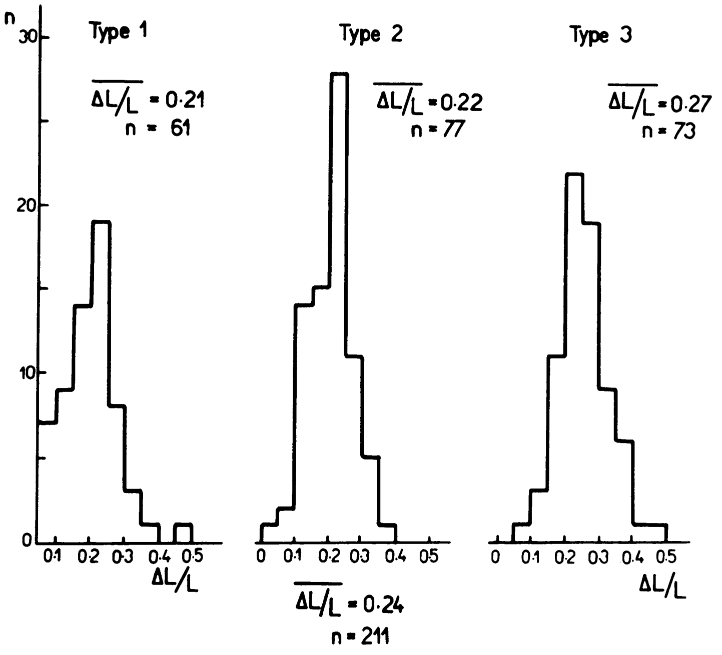

FIG. 3. *Histograms of relative ring thickness for each classification type separately.*

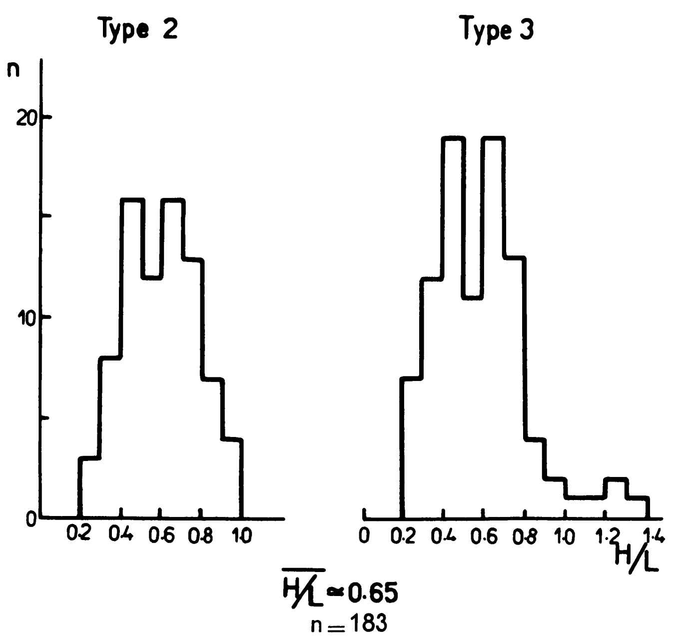

FIG. 4. *Histograms of relative ring heights for two classification types separately.*

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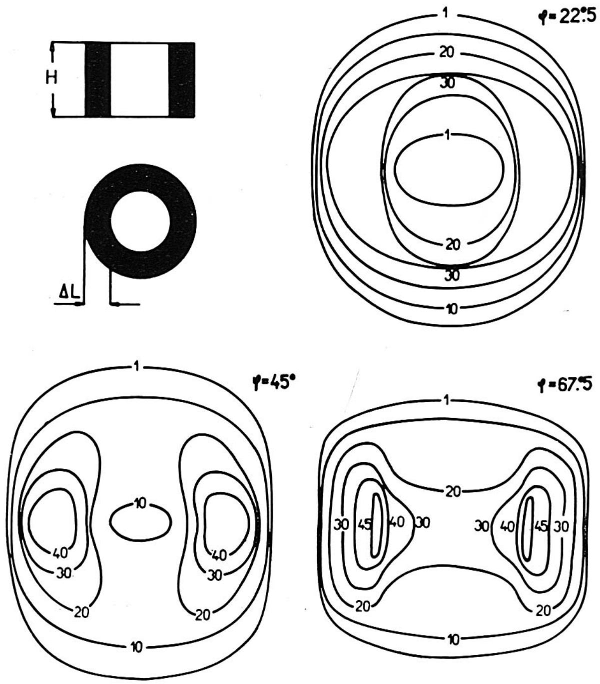

FIG. 5. *Computed isophotes for model structure with mean parameters derived from observed planetaries.*

It is interesting to compare observed numbers of nebulae of different classification types with those predicted on the basis of our isophotal pictures. Looking at the isophotes one can see that the critical angle which separates the ring-shaped nebulae from the other forms is about 30°; Table 2 contains the predicted and observed numbers of the nebulae of different types.

Table 2

Relative numbers of planetary nebulae of different types

Type of the main structure	1	2 + 3
Theory	1·0	6·1
Observations	1·0	2·3

It is evident that while a qualitative agreement between the theory and observations does exist, there is still a significant observational excess of the type-1 objects. This excess can be explained as a result of observational selection, in that very faint type-1 objects can be more easily distinguished on photographic plates than irregular type-3 objects. This interpretation can be proved by the dependence of the distribution of objects of different types on their surface brightness and on their galactic latitude. The first of the distributions clearly shows a decrease of the fraction of fainter nebulae from type 1 to type 3. The second one demonstrates a relatively higher degree of concentration of type-3 objects to the galactic plane; hence these objects are more distant and consequently brighter and more compact as well. One of conclusions following from this reasoning is that some dozens of extremely faint and nearby type 3 objects still remain undiscovered.

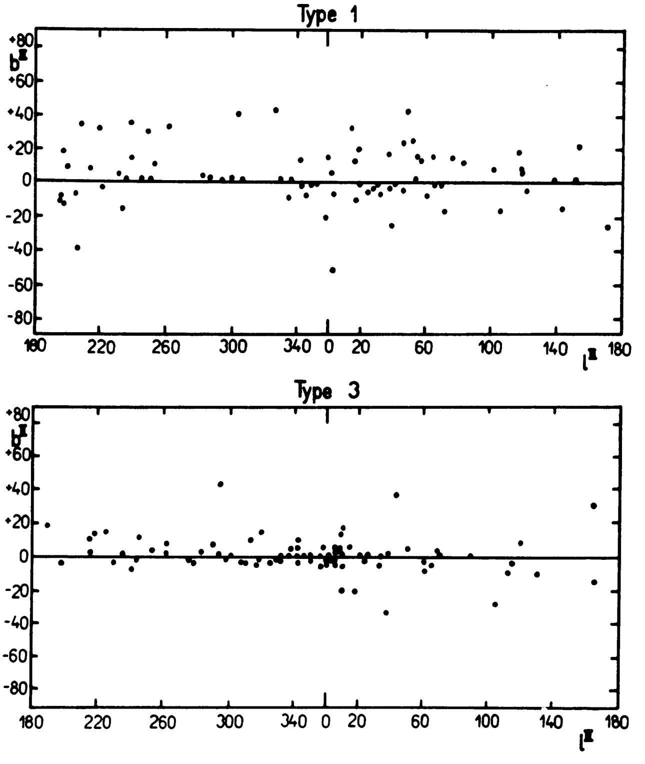

FIG. 6. *Galactic distribution of type-1 and type-3 planetaries separately.*

Let us consider now the peripheral structures of planetary nebulae. According to our classification there are three observed types of these structures. It is interesting to note that relatively regular, ring-like structures of type *d* are seen exclusively around regular ring-shaped type-1 main structures. It is seen in addition that type-*b* structures frequently appear about type-2 and type-3 nebulae, and that the outer diameter of a type-*b* structure usually exceeds that of its corresponding main structure. Considering the situation in terms of projection, one can conclude that regular type-*d* peripheral structures appear due to the projection of type-*b* structures, so the structures of type *d*

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do not represent an independent morphological case. An analogous idea has been expressed earlier by Minkowski and Osterbrock (1960) with respect to the nebulae NGC 650-1 and NGC 6720.

The latter conclusion can be supported by a comparison of numbers of planetary nebulae with the peripheral structures of *b* and *d* types. The ratio $N(2b+3b+3ab)/N(1d)=2{\cdot}7>1$, as it should be according to the general law of projection. It is worthwhile to mention as well, that the average diameter of type-*d* structures and the average *maximum* width of type-*b* and *ab* structures show a good deal of agreement: $l/L(1d)=1{\cdot}9$, $l/L(3b+3ab)=1{\cdot}5$.

It is interesting to note that, while the overwhelming majority of so-called double-shell planetary nebulae can be interpreted in the framework of the picture outlined above, some examples of real double-shell nebulae still exist. The fraction of them is rather small but not negligible. The typical samples of such objects have outer symmetrical condensations in the equatorial plane of the main structure. They are seen most distinctly among the type-3 nebulae, among which there are two definite cases of nebulae of this kind.

At the same time the difference between type *a* and type *b* is real. Trying to find any physical differences between the nebulae possessing these two kinds of peripheral structures we have studied in detail appropriate observational data. It is evident that type 3 nebulae offer the best opportunity to study peripheral structures. The mean observed galactic latitude of 3b nebulae is $|b^{II}|=3\overset{\circ}{.}7$, while that of 3a objects is $9\overset{\circ}{.}9$. It means that the mean distances of 3a and 3b objects differ by about the factor of 2·7. Taking into account the mean angular diameters of these objects ($\varphi(3a)=75''$, $\varphi(3b)=20''$), one can estimate that the ratio of their mean linear diameters is about of 1·4; this difference is thus not very significant.

The surface brightnesses of 3a objects are approximately by 1^m lower than that of 3b objects. The different character of the galactic concentration of type 3a and 3b nebulae may indicate that our observational data on these nebulae have been affected by a factor of observational selection.

There are perhaps two possible ways of further discussion. The first one states that the only small difference in linear diameters of type 3a and type 3b nebulae most likely indicates their age to be approximately the same. Then the whole variety of *a* and *b* structures could reflect different dynamical conditions in the respective nebulae – probably different shapes of the velocity field. (This point of view is shared by L.K.)

The second approach is based on the supposition that the small difference between the surface brightness of type 3a and 3b nebulae actually reflects the fact that the density in 3b objects is approximately 2·5 times that of 3a objects. And, vice-versa, we may suppose that planetary nebulae with an *a*-type periphery represent an older evolutionary stage of 3b objects. (This second point of view is shared by G.S.K.)

In conclusion we would like to consider briefly some dynamical consequences following from the foregoing spatial model of planetary nebulae. These consequences are as follows:

(1) The expansion velocity field in planetary nebulae must have axial symmetry.

(2) The expansion velocity must increase from the equatorial plane of the main structure to its poles.

(3) The direction of the maximum-velocity vector may not necessarily coincide with the polar axis. In fact, most elongated details of type-*b* peripheral structure are usually directed at an angle to the polar axis.

(4) The equatorial expansion velocities must be at least two times smaller than those in the polar region. (This conclusion is based on measurements of the relative extensions of these structures.)

(5) The character of the expansion velocity field probably is subject to evolutionary variations.

The expansion of a planetary nebula plays the role of the principal evolutionary factor. This expansion causes a density decrease, which in turn promotes the process of ionization of the nebula. An ionization front moving outwards through the nebula must significantly affect the original velocity field and the density distribution. One may suppose that nebulae with type-*b* peripheral structures are objects in which the process of ionization is almost finished, while nebulae with type-*a* structures are completely ionized objects.

To explain the origin of the toroidal structure of planetary nebulae, one has to search for a source of a primeval axially symmetric instability. We can suggest a mechanism which can probably explain the observed picture. If in a primeval planetary nebulae there is a slight concentration of density in the equatorial plane, it will focus the ionization front. As a result this inhomogeneity will be increased and something like the observed toroidal structure will appear. A similar result could be obtained on the supposition that the primeval velocity field originally had an axial symmetry. The proposed qualitative mechanism is very schematic, and further theoretical and observational investigations of the dynamics are needed.

In conclusion we would like to note that a detailed and more accurate account of this morphological study, together with discussion of peculiar observed forms of planetaries is to be presented in two or three papers in the *Bulletin of Astronomical Institutes of Czechoslovakia* in the beginning of next year.

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