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Abstract

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NEW DOUBLE-SHELL PLANETARY NEBULAE

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At present it is almost obvious that all planetary nebulae, beginning with a definite stage of their life, must be double-shelled (type II) ([1]); before this they consist of only one shell (type I). The appearance of a second shell around the main one is explained by the peculiar behavior of the light pressure inside the nebula, caused by L_α-radiation ([2,3]). Since the second (outer) shell expands faster than the main (inner) one, at a certain moment the surface brightness of the second shell reaches the threshold of visibility, and it becomes invisible. The remaining part of the nebula (the inner or main shell), expanding sufficiently, assumes a ring-shaped form (type III). Thus, the double-shell phase of a planetary nebula is transitional from planetary-like to ring-shaped.

The process of separation of the second shell from the main one occurs during that period in the life of the nebula when its optical thickness τ_c at ultraviolet frequencies is appreciably greater than unity (of the order of 5-10), and its dimensions are of the order of 5-10 thousand AU (in diameter). When the nebula is already double-shelled, τ_c becomes considerably less than unity, and the dimensions of the nebula are considerably larger than the indicated value. Therefore, a good test of the theory could be provided by establishing through observations the existence of a very faint second shell in relatively large planetary nebulae, especially in ring-shaped nebulae.

Usually the second shells are very faint, and therefore they should be sought on photographs obtained with powerful, fast telescopes and with the use of long exposures. The image of the main shell in such photographs is most often strongly overexposed.

Table 1

Nebula	d_1	d_2	d_2/d_1
NGC 1514	$120'' \times 90''$	$180'' \times 150''$	1.5
NGC 2610	$33'' \times 31''$	$60'' \times 50''$	1.6
NGC 4361	$70''$	$110''$	1.6

Nebula	d_1	d_2	d_2/d_1
NGC 6058	$25'' \times 20''$	$40'' \times 30''$	1.6
NGC 6369	$28''$	$60''$	2.1
NGC 6445	$38'' \times 29''$	$150''$	~ 4
NGC 6543	$22'' \times 16''$	$300''$	~ 15
NGC 6853	$470'' \times 350''$	$\sim 700''$	1.5–2

Note. d_1 for all nebulae, except NGC 4361, is taken from ([5]).

A rich body of material on the question of interest to us was collected when we examined the sky-survey charts of the Palomar Observatory. Already according to preliminary data, **the existence of a second shell has been established in 10 planetary nebulae**, which previously were not known as double-shelled and had been classified as single-shelled (planetary-like) or else ring-shaped. The basis for searching for a second shell in these nebulae was either their large dimensions or else a noticeable ring-shapedness of form. In Table 1

a list is given of planetary nebulae for which the existence of a second shell has been established for the first time and with certainty*. There the visible dimensions of the inner (d_1) and outer (d_2) shells are also given, as well as the values of the ratio d_2/d_1, which is independent of the distance of the nebula from us. In Fig. 1 reproduction photographs of some of these double-shell nebulae are given. In addition, there are at least two more nebulae—NGC 7008 and anon. 22^h17^m—in which faint traces of a second shell are noticeable.

Among the objects listed in Table 1, the nebula NGC 6543 is of particular interest. Until now it was known that this is only a spiral-shaped, or, according to the original classification, helix-shaped nebula (the most recent photograph of this nebula, obtained with the 200-inch telescope, is given in paper ([6])). It now turns out that it is surrounded by a faint, very extended second shell of regular form, but, judging from the photograph (Fig. 1b), with a clearly expressed fibrous structure. The ratio d_2/d_1 for this nebula, approximately equal to 15, proved to be the largest among all double-shell nebulae known so far. The smallest value of d_2/d_1, equal to 1.16, was established for the nebula NGC 3587. These data show that there is great diversity in the physical conditions that determine the formation of a second shell as a result of the separation of part of the mass from the main shell.

According to the theory of the formation of double-shell planetary nebulae (([2]), p. 164), the difference between the diameters of the two shells is, in first approximation, proportional to the fourth power of the temperature of the nucleus T_* and inversely proportional to the square of the expansion velocity of the nebula v_0 (the main shell). Hence it is not difficult to derive

$$\frac{d_2}{d_1} = 1 + C\frac{T_*^4}{D_1 v_0^2}, \tag{1}$$

where D_1 is the linear diameter of the main shell, and C is a certain constant. From this relation it follows that a large value of d_2/d_1 may be a consequence either of a high temperature of the nebular nucleus or of a low expansion velocity. With regard to NGC 6543 it is known that it is expanding with a comparatively small velocity: according to Zanstra' s measurements, $v_0 = 12$ km/sec ([7]). As for the temperature of the nucleus, it, determined from the ratio of the line intensities $N_1^+ N_2/\lambda 3727$, is of the order of 60 000° ([8]), i.e., comparatively high; this is also indicated by the presence of a very intense $\lambda 4686$ He II line in its spectrum (type WC + WN) ([9], [10]).

Furthermore, despite noticeable fluctuations in brightness, the mean surface brightness of the second shell is almost constant over the whole nebula. This may serve as an indication that the second shell in the case under consideration is a full sphere, rather than a thin shell. In other words, if the space between the two shells is filled with gaseous matter, then its density is considerably lower than the density of the matter of the second shell. Incidentally, this peculiarity is characteristic of most double-shell planetary nebulae.

A sufficiently bright and regular-shaped second shell was also discovered in the well-known spiral planetary nebula NGC 4361 (in the large-scale photograph of this nebula given in ([6]), only faint traces of the second shell are visible).

Along with the discovery of new double-shell nebulae, new evidence was obtained, in addition to that given earlier ([11], [12]),

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* The existence of a second shell in the nebula NGC 6853 had been established earlier by N. A. Razmadze in a photograph obtained with the large meniscus telescope of the Abastumani Observatory.

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Fig. 1. Planetary nebulae: *a* –NGC 1514 (reproduction 8.5 ×); *b* –NGC 6369 (reproduction 10 ×); *c* –NGC 6543 (reproduction 5.8 ×)

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Fig. 1. Microphotographs of cleavages along the basal plane, obtained upon fracture of amalgamated zinc single crystals with $\chi_0 \sim 30°$; 40 ×

of the existence of typically planet-like (type I) nebulae without a second shell. Thus, for example, the nebulae NGC 6572 and NGC 6894, which possess high surface brightness, appeared on the Palomar charts as strongly overexposed, but without any traces of a second shell. Second shells are absent in the star-like planetary nebulae NGC 2452 and NGC 6778. Apparently, the nebulae NGC 6842, 7048, A39 (according to Abell' s list (4)), A43, A54, etc., are also purely planet-like.

Until recently the list of double-shell planetary nebulae consisted of 17 objects ((2), p. 205). Now this list contains about 30 well-verified objects. This means

that almost one-third of all planetary nebulae for which more or less successful photographs are available are double-shell nebulae. This circumstance also indicates that the double-shell phase is a regular phenomenon for all planetary nebulae.

In this connection it should be noted that the term "ring-shaped" for planetary nebulae is nevertheless conventional, and it may continue to be accepted only from the standpoint of convenience in classifying them. In contrast to planet-like nebulae, which in reality consist of a single shell, ring-shaped nebulae consist of two actually existing shells, and only because of observing conditions do they appear to be single-shell objects. If we could photograph all large, low-surface-brightness, ring-shaped planetary nebulae in such a way that their second, fainter shells appeared, then, probably, we would speak only of single-shell planet-like and double-shell planetary nebulae. **Every planetary nebula is born as a single-shell object, but ends its life as a double-shell object.** This is one of the important features of the evolution of planetary nebulae.

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