

PLANETARY NEBULAE, SURVEY AND OUTLOOK*

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Introduction

Attention was drawn to planetary nebulae originally as a consequence of their pictorial interest and the unusual nature of their spectra, which attracted devotees of the then new field of atomic spectra — among them I. S. Bowen, H. Zanstra, and D. H. Menzel. It was realized half a century ago that the central stars were precursors of white dwarfs — objects already recognized as the last stage of stellar evolution.

An immense observational step forward was made by the physicist-turned-astronomer whose memory we honor in this symposium. Rudolph Minkowski greatly extended our knowledge of planetary nebulae by discovering many new ones (1946, 1947, 1948, 1953), by investigating their space distributions and distances (1951, 1965), by securing high-resolution monochromatic photographs of many of the most interesting of these objects (1968), and by detailed studies of their spectra (1942; Minkowski and Aller 1956). In this review I plan to emphasize those areas of nebular research in which Minkowski made important contributions.

Why are planetary nebulae important and what can they contribute to broader problems of galactic structure and stellar evolution?

1. They are widely distributed throughout the galactic system and are found in external galaxies, even though they are not among the most luminous objects found therein.

2. They represent a well-defined stage in stellar evolution that immediately precedes the white dwarfs. Far from being objects removed from the main stream of astronomy, they represent phases through which many (if not the vast majority) of stars pass.

3. Thus the chemical compositions of planetary nebulae assume special interest. Do these envelopes arise solely from outer strata of the star and are they therefore untainted by the products of internal nuclear reactions so that they thus reveal the chemical composition of the interstellar medium from which the star was formed? Or, alternately, have the evolving stars ejected their envelopes after a considerable amount of mixing has taken place, so that the chemical composition shows the telltale marks of nucleosynthesis involving lighter elements such as nitrogen or helium?

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If the former situation prevails, planetary nebulae can serve as powerful tools for getting abundances of helium, nitrogen, oxygen, neon, etc., in the ancient interstellar medium of elliptical galaxies — information which cannot be extracted from integrated stellar spectra.

Alas as tools for such investigations, planetary nebulae suffer from severe disadvantages. First, the distances of nearly all individual objects remain poorly determined. Second, chemical compositions are difficult to establish, primarily as a consequence of the extreme inhomogeneity of these objects and the difficulty of allowing for distribution of atoms among different ionization stages (see, e.g., Aller and Czyzak 1973).

The question of the ancestry of planetary nebulae remains puzzling. What percentage comes from the old-disk or spiral-arm population and what percentage comes from Population type II? Clearly, the halo planetary described by Miller (1971) and the one in M15 (Peimbert 1973) certainly belong to Population II. Others such as BD +30°3639 appear to belong to Population type I. Greig (1971, 1972) divided planetaries into two classes on the basis of their morphology and forbidden lines of [O I], [O II], and [N II], which are strong in his class B but weak in his class C. Class B objects tend to have more filamentary structure and to arise from younger disk or spiral-arm stars. Class C objects presumably are associated with Population type II.

Distances

Minkowski (1965) critically reviewed the distance determinations that had been made up to the mid-sixties. Pioneering efforts had been undertaken by Parenago, Zanstra, and Vorontsov-Velyaminov, but we must cite especially the outstanding contribution by L. Berman (1937). In his 1965 review, Minkowski compared estimates of nebular distances on two assumptions: (a) that the absolute magnitude is constant, r_L , and (b) on the assumption that the mass of the luminous shell is constant, r_M (Shklovsky hypothesis). For an optically thick nebula r_L tends to be more nearly correct. On the other hand, if nebular masses are approximately constant, an incompletely ionized nebula would be placed at too great a distance, i.e., r_M would be too large. Alternately, the distance of an optically thin nebula ought to be closer to r_M , and

r_L would exceed r_{gr} . Thus, r_L/r_{gr} serves as a discriminant. More elaborate procedures were proposed by Seaton (1966, 1968*b*). Cahn and Kaler (1971) obtained distances (or upper limits to the distances) of more than 600 planetaries by method (b) above, combined with a model of the galaxy designed to take into account the dust distribution in a self-consistent fashion.

Angular expansions (cf. e.g., Liller, Welther, and Liller 1966; Liller and Liller 1968; Latypov 1955; Chudovicheva 1964) have been used to obtain distances for a few relatively nearby objects. Mrs. Lutz (1973) has used interstellar extinction as a tool for getting nebular distances, while Mottman (1972) has challenged the assumption that nebular shells have constant masses. Binaries among planetary nebulae may prove to give some of the most reliable distances.

Recently, Cudworth (1974), employing new proper motions measured at Lick, has rediscussed the statistical parallaxes and distances of planetary nebulae. His distance scale for optically thin nebulae agrees with that of Seaton (1966) and appears to be in satisfactory accord with other determinations. He treated Greig's classes B and C separately and concluded that Mira-type variables were the progenitors of planetary nebulae. Judging from their spatial distribution perpendicular to the galactic plane, the progenitors of Greig's class B presumably had masses of the order of 1.5 solar masses, while those of type C had masses less than one solar mass. The class B objects tended to move in more nearly circular galactic orbits.

More accurate proper motions will become available as time goes on, so that our knowledge of kinematics and distance scales should improve, but it is likely to be a long time before distances of individual objects will be accurately established. Masses of individual nebular shells almost certainly vary. Cudworth suggested a mass of about 0.5 suns for a typical planetary; on the other hand the mass of the M15 planetary appears to be about $0.02 M_{\odot}$. A mass range of a factor of ten or more introduces an intolerably large error in distance determinations via the constant-mass hypothesis.

Role of Density and Temperature Fluctuations

In recent years a vast amount of work has been done on the spectra and structure of planetary nebulae. Symposia were held at Tatranska-Lomnica in 1967, in Liege in 1972, and another is scheduled at Cornell in 1977. Unfortunately, in much of the discussion of physical conditions in planetary nebulae, the consequences of filamentary structure and stratification have been ignored. Minkowski's (1968) comments at the 1967 symposium are worth recalling.

"One of our most urgent problems is

is that of trying to assess the consequences of picturing a planetary nebula as an envelope or a shell with a constant density, constant ionization, and constant electron temperature. . . . We should try to estimate at least the order of magnitude of the errors that are now being committed by total disregard of the properties or real planetaries.

"The photoelectric observations which are our most reliable source of information on flux densities in the emission lines, and many photographic observations give us values integrated over the whole nebula . . . to assess effects of filaments and condensation on the analysis of the results, we must know the conditions of these features. We need reliable spectrophotometry of small details and local areas. Even such observations give no more than an integral over the line of sight through the nebula. Differential observations of condensations and their surroundings are necessary to ascertain the conditions in condensations."

Minkowski then went on to point out that discordances between photographic and photoelectric measurements did not necessarily mean that the latter are OK and the former are inaccurate, but rather that differences may reflect the influence of knots and condensations. Turning to theoretical interpretations, he said

"Even crude models of inhomogeneities may be useful for estimating the errors that may arise from unrealistic and oversimplified descriptions of a planetary nebula . . . such errors may be very large . . . how much can we really trust for instance the evolutionary track derived for the central star?"

In addition to Minkowski's epoch-making photographs obtained with the Hale telescope, a vast amount of direct photographic and spectrographic evidence (Capriotti, Cromwell, and Williams 1971; Aller and Walker 1970) shows that even in relatively smooth looking objects, filamentary fine structure is present.

Peimbert (1967) proposed an elegant method for handling the influence of temperature fluctuations on the excitation of nebular lines and the derivation of chemical abundances. The method is appropriate for the frequently encountered situation where we can observe only the integrated light of the nebula. Crucial observational parameters are the rms temperature fluctuations, $\langle(T - T_0)^2/T_0\rangle^{1/2}$, and temperatures

found from individual line ratios. Many investigators have employed the Peimbert formulation.

Recently, Boeshaar (1975) has attempted to construct empirical models in which small-scale changes in ionization, temperature, and density within the source are taken into account. The method needs to be refined, particularly in handling properties of the ionizing radiation field.

Spectroscopic Studies

I would like to describe a continuing spectroscopic program, concerned with a number of mostly bright planetary nebulae, carried out at Lick and Mount Wilson Observatories, in collaboration with S. J. Czyzak of Ohio State University, J. B. Kaler of the University of Illinois, and my colleague H. W. Epps. There are three aspects:

1. Photographic spectra obtained with as high resolution as possible in the region 3100 Å to 5100 Å.
2. Image-tube scanner (ITS) observations with the 3-m telescope at Lick Observatory, in the range 3700 Å to 8600 Å.
3. Photoelectric spectrophotometry on the strongest lines to provide a suitable calibration both for the ITS and photographic results, so that in particular, we need only use the photographic plate as an interpolation device.

Unfortunately, this third program (which was carried out at Mount Wilson) was cursed with atrocious weather after 1971 and we were forced to abandon it. In addition, observations of the central stars have been carried out (Smith and Aller 1969; Aller 1968, 1976); the earlier spectroscopic observations which concentrated mostly on regions shortward of $\lambda 5000$ have been supplemented by ITS data.

The objective of the nebular program was to obtain as detailed diagnostic information as practical by observing each element as in many stages of ionization as possible, and to examine nebular regions of differing excitation. Although methods other than photographic spectrophotometry usually are to be preferred, the high resolution of the photographic plate often permits us to detect weak, diagnostic lines of great importance, e.g., the [Ne IV] features near $\lambda\lambda 724, 25$ which can be of considerable significance in assessing the excitation level of a nebula.

The first phase of this program was a comprehensive new investigation of the spectrum of NGC 7027 (Kaler et al. 1976) to replace earlier work (Aller, Bowen, and Minkowski 1955; Aller, Bowen, and Wilson 1963) which was based largely on photographic photometry. We critically surveyed all published data in the wavelength range $\lambda 3100$ – $\lambda 8670$. For wavelengths longward of $\lambda 5100$ we have relied heavily on ITS results calibrated by Mount Wilson photoelectric spectro-

photometry.

To illustrate the type of scans obtained in this investigation, let us examine some data for NGC 7009 (see Figs. 1 and 2). Many years ago, Berman (1930) made the first quantitative study of excitation differences in this beautiful nebula. Ionization is higher along the minor axis, whose spectrum has been studied in great detail, but is low along the major axis in the bright ring, and in the ansae. In each location, the strongest line in this spectral region is $\lambda 5876$ He I. Along the major axis note the strong [O I], [N II], [Cl III], and [S III] lines; $\lambda 5411$ He II is only moderately strong. On the minor axis, O I has disappeared, [N II] and [Cl III] have weakened, C IV has appeared, but He II is very strong. Note the metallic forbidden lines: [Fe III], [Fe VI], and [K IV] that appear in both spectra. Similar scans have been obtained for other nebulae. We may anticipate obtaining the same chemical composition for different parts of the same nebula if our procedures for calculating elemental from ionic abundances are correct. For objects such as NGC 7009, it would appear that improvements in the theoretical treatment are needed (Aller and Epps 1975).

The [N II] lines play a particularly important but elusive role in the spectra of planetary nebulae. Long ago, Wyse (1942) called attention to the capricious behavior of [N II] which sometimes attained great strength in high-excitation nebulae where such low-excitation features were scarcely to be expected. We now attribute this behavior to the existence of dense knots and condensations of high density and low ionization. As shown in Figure 3, the [N II] lines sometimes dominate the spectra of objects of low surface brightness such as NGC 6537 whose remarkable, irregular structure is revealed by Minkowski's direct photographs. For photographs and isophotic contours see Aller and Liller (1968) and Aller (1956). A more familiar example is the Ring nebula, NGC 6720. In Figure 4 we compare the [N II] lines and H α at two positions in the ring with two positions in the interior near the central star. In the latter settings we see contributions from both the outer shell and the central regions. Probably the [N II] lines originate mostly from the outer shell.

Electron densities and temperatures were found from ITS measurements of the [N II], [S II], and (where possible) the [Cl III] lines at several points in the ring and interior region (Aller, Epps, and Czyzak 1976). This reconnaissance also employed $\lambda 3729/\lambda 3726$ [O II] ratios (Minkowski and Osterbrock 1960) and $\lambda 4363$ [O III] and [O II] $\lambda 3727$ intensities obtained with the Lallemant tube (Aller and Walker 1965). A more consistent and satisfactory procedure is to use *only* ITS data obtained at the indicated positions in the nebula, rather than the Lallemant tube

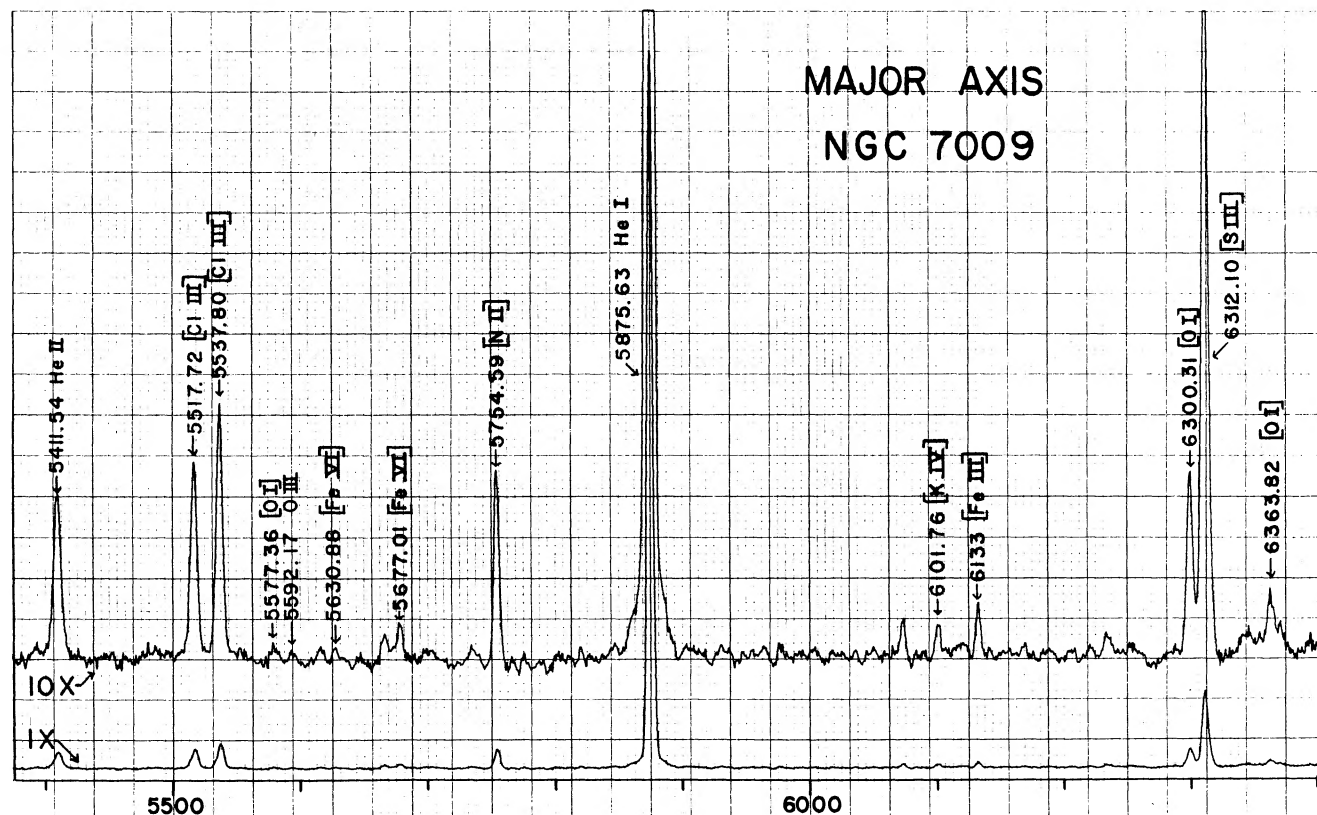


FIG. 1 — Scan of the bright ring in NGC 7009 on the major axis. The tracing has been corrected for paired pulses, instrumental response, and deviations of the dispersion from linearity. The two scans differ by an amplification of ten. Data were obtained with the image-tube scanner, Lick Observatory.

or other spectroscopic data which involve some averaging over position in the nebula. The data given in Table I are based only on our ITS data. Chemical compositions for the ring and interior inferred from ionic concentrations by the usual procedures (Seaton 1968*b*; Peimbert and Costero 1969; Kaler 1970; Peimbert and Torres-Peimbert 1971; Aller et al. 1973) tend to give abundances in general agreement with those found by Hawley and Miller (1976), who measured somewhat different positions in NGC 6720. In region no. 10, we also find an apparently enhanced neon abundance, again consistent with their results. Within the different regions, essentially the same abundances are found to within a factor of about two; such differences can easily result from slight changes in the assumed temperatures. The mean abundance quoted in Table II ought to be meaningful.

One hopes that it will be possible to construct a realistic model that will handle the radiation field, ionization equilibrium, etc., in a reasonably accurate fashion for such objects. The task will not be easy. The wonderfully detailed information on point-to-point [O III] temperature changes over the surface of NGC 6720, obtained by Goad (1975) emphasizes some of the difficulties involved. His narrow-band inter-

ference photographs suggest a two-component model consisting of a tenuous diffuse nebular medium and a network of dense knots and filaments whose inner edges are illuminated by the central star. Goad suggests that the inner regions of nebulae such as NGC 40 or NGC 6720 appear to be hollow, scoured out by a stellar wind blowing from the central star. In other nebulae, as well as in NGC 6720, enhanced [N I] and [N II] intensities tend to occur together (Aller and Walker 1970).

A big problem is how to allow for unobserved stages of ionization in elements such as nitrogen which are represented by only one or two ionization stages. At present, the best procedure might be to use models such as those suggested by Flower (1969), Harrington (1968, 1969), Kirkpatrick (1970), or Buerger (1973) but with suitable refinements. For nitrogen itself, the problem may be alleviated eventually if we are able to observe the infrared [N III] emission with a spectrograph in a space telescope.

The aforementioned extrapolation procedures appear to work better for low-excitation objects than for high-excitation ones. In a nebula showing [Ne IV] and with strong [Ne V] lines, one calculates a neon abundance that is typically about three times higher

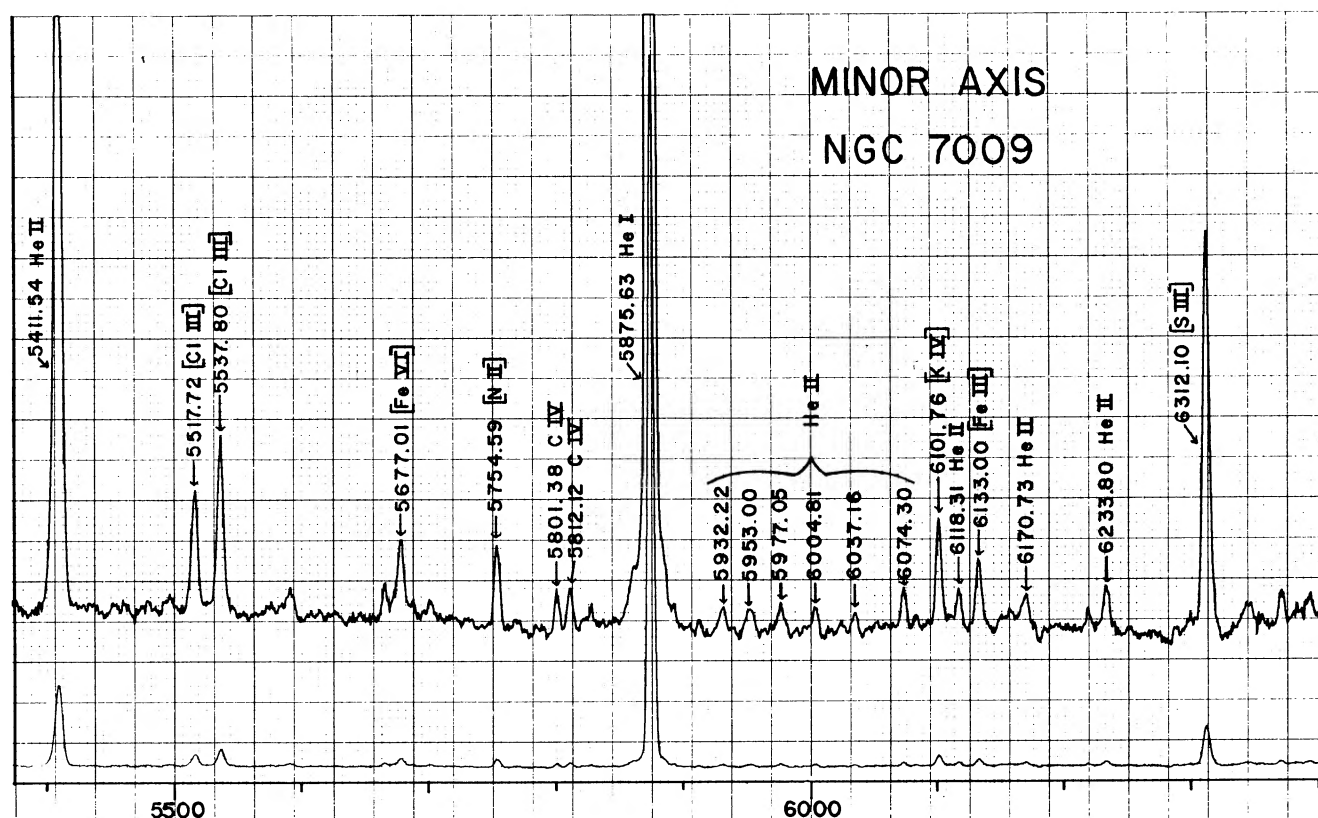


FIG. 2—Scan of the bright ring in NGC 7009 on the minor axis. The tracing has been corrected for instrumental effects etc., as in Figure 1. Amplifications of one and ten are employed. Data were obtained with the image-tube scanner, Lick Observatory.

than indicated by extrapolation from the [Ne III] abundance and the $n(\text{He})/n(\text{He}^+)$ ratio. Hence, the Seaton procedure for extrapolating the oxygen abundance from $n(\text{O}^{++})$ is questionable for high-excitation objects. In nebulae such as 86 – 8° I theoretical nebular models offer more hope than quasi-empirical extrapolation procedures, even though we observe more stages of ionization of Ne, C, Ar, etc., than in most planetaries. We are examining this point further.

Table II gives abundances derived by these extrapolation methods for a number of planetary nebulae ranging in excitation level, total brightness, galactocentric coordinates, etc. The first column gives the designation of the object, the second the adopted distance from the galactic center computed from Cudworth's (1974) results on the assumption that the distance of the sun from the galactic center is 10 kpc. For a few nebulae I have employed photometric distances derived on the thin-shell approximation (Milne and Aller 1975). The following columns give the derived abundances on the scale wherein the logarithm of the hydrogen abundance is 12.00 i.e., $\log N(\text{H}) = 12.00$ and the last column gives references to the literature. In some instances, values are quoted from previous work: NGC 40, NGC 6445, NGC 6803, NGC 7009, NGC 7662, IC 418, and IC 4593. In other

cases published work has been consulted in connection with analysis of the ITS data, but in most instances the ITS data supplemented by photoelectric scanner measurements have been preferred. Full details will be given elsewhere.

The Peimberts (1971, 1974, 1976) have discussed the question of abundance differences that may arise from nuclear reaction in the stars themselves. First of all, we might expect nitrogen to be enriched with respect to oxygen. From stellar models of red giant stars (Iben 1965, 1966, 1967) Torres-Peimbert and Peimbert (1971) predict that during the red-giant phase of stellar evolution, nitrogen-enriched material from the carbon-nitrogen cycle in the hydrogen-burning shell gets mixed into the convective envelope and conveyed to the surface. The N/O ratio enhancement is not very sensitive to the stellar mass but depends on the heavy element fraction (Z value). Adopting $\log(N/\text{O})_{\text{solar}} = -0.90$ (Ross and Aller 1976), we find the predicted enhancement $[N/\text{O}] = \{\log(N/\text{O}) - \log(N/\text{O})_{\text{solar}}\}$ to be about 0.5. Boeshaar (1975) concluded that the nitrogen enrichment in planetaries is at least as great as that which had been suggested by the Peimberts. From our data for planetary nebulae, we find $[N/\text{O}] = 0.32$ for Greig's "B" nebulae and 0.15 for his "C" nebulae. The accuracy of these num-

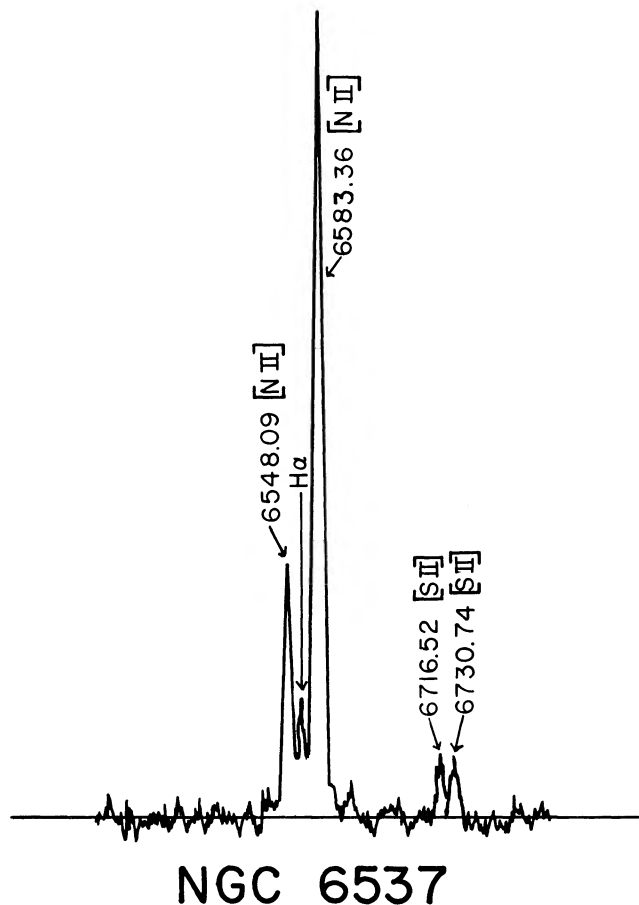


FIG. 3—A tracing of the neighborhood of $H\alpha$ in NGC 6537. This nebula has a low surface brightness. Note the great strength of the $[N II]$ lines compared with $H\alpha$.

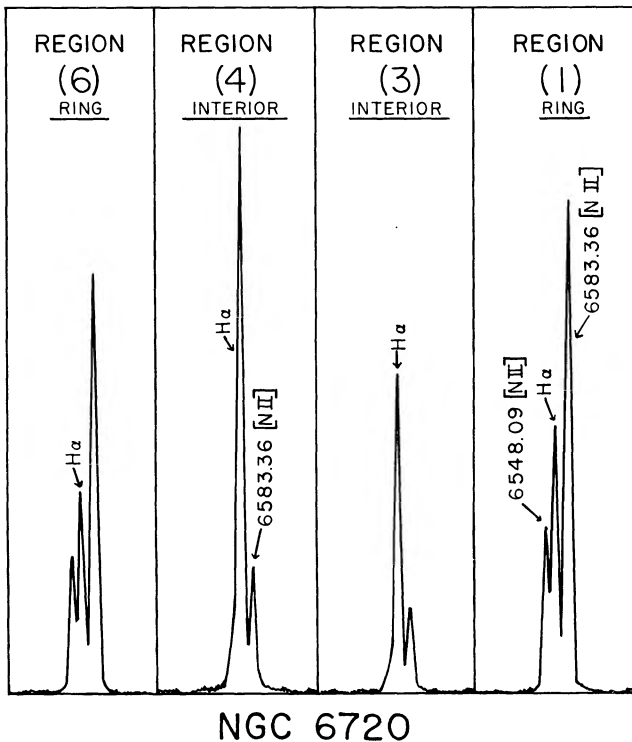


FIG. 4—Tracings of the $[N II]$ and $H\alpha$ lines in the Ring nebula. The numbers (1)-(6) refer to positions marked on the chart in Aller, Epps, and Czyzak (1976). Note the great strength of $[N II]$ in the ring as compared with $H\alpha$, whereas the reverse is true when we look into the central regions.

TABLE I
DERIVED ABUNDANCES FOR FIVE TYPICAL REGIONS IN THE RING
AND INTERIOR OF NGC 6720

Position	(1) N. Ring	(3) Interior	(4) Interior	(6) S. Ring	(10) E. Ring
Adopted					
T_e [O III]	10,200	10,200	11,500	10,200	10,200
T_e [N II]	10,200	9,800	9,500	10,200	10,200
x	0.13	0.13	0.08	0.25	0.10
$\log N$					
He	11.00	11.02	11.01	11.02	10.98
N	8.53	8.21	8.21	8.36	8.31
O	8.90	8.86	8.87	8.83	8.87
Ne	8.39	8.23	8.10	8.39	8.74
S	7.51	7.67	7.52	7.29	7.59
Cl	5.62			> 5.4	
Ar	6.57	6.65	> 6.19	6.55	

The numbers (1), (3), etc., denote observed regions as indicated on the chart given by Aller, Epps, and Czyzak (1976). The electron temperatures for the [O III] and [N II] lines are obtained from the ITS data for $\lambda\lambda 4363, 4959, 5007, 5755, 6548$, and 6584 , respectively. The x -values are adopted from the [S II] $\lambda\lambda 6717/6730$ and the [Cl III] $\lambda\lambda 5517/5537$ ratios, influenced by the [O II] results by Minkowski and Osterbrock (1960). The mean value for neon quoted in Table II excludes region 10.

TABLE II
ELEMENTAL ABUNDANCES IN PLANETARY NEBULAE
Log N

Object	R	He	N	O	Ne	S	Cl	Ar	Refs.
NGC 40	11.0		7.43	7.87	6.76	6.27			(1)
			7.87	8.60	7.5	6.83			(2)
IC 1747	12.3	11.00	7.95	8.56	7.93	7.32		6.23	(3)
IC 351	17.3	10.96	—	8.74	8.07	—	>4.4	6.20	
IC 2003	14.36		(7.83)	8.55	7.81	7.32	5.8:	6.31	(4)
NGC 1535	12.3	11.04	—	8.30	7.55		>4.2	>6.17	
J320	18.9	11.032	7.23	8.15	7.47	7.3:		6.84:	
IC 418	10.1	11.2?	7.6	8.4	7.49	7.0	>5.2	6.7	(5)
IC 2165	13.54	11.043	7.63	8.43	8.07	7.44	>5.38	>6.2	6
NGC 2371-72	12.4	11.096	8.15	8.73	8.03	7.4:	>5.3	≥6.53	
NGC 2452	11.53	10.99	8.52	8.62	8.02	8.2:	>5	≥6.61	
			7.74	8.43	7.80	7.0		6.0	(5)
IC 3568	12.2	11.075	7.54	8.29	7.53	—	>4	>5.7	
IC 4593	7.7	11.083	6.31	8.37	7.6	7.2:		6.0	5,7
NGC 6210	9.14	11.00	7.63	8.70	8.02	7.53	>4.81	6.30	8
NGC 6302	7.52	11.29	8.8:	8.66	8.23	7.68	5.54	6.76	9
NGC 6309	5.83	11.097	7.96	(8.80)	8.28	7.12	≥5.49	>6.51	(3)
NGC 6445	8.72	11.34	8.15	8.43	8.04	7.70		>6.18	(10)
NGC 6543	10.2	10.98	8.11	8.71	8.05	7.86		≥6.5	11
NGC 6720	9.5	11.00	8.32	8.87	8.28	7.52	>5.2	6.59	
NGC 6741	13.0	11.065	8.18	8.91	8.46:	8.04	>5.1	6.75	12
NGC 6751	7.6	10.95	8.29	8.78	8.01	7.39	5.46	≥6.38	
IC 4846	6.2	10.99	7.85	8.73	7.92	7.87		>5.93	
NGC 6778	7.93	11.12	8.70	8.70	8.12	7.56	5.65	>6.55	13
NGC 6790	7.5	11.08	7.97	8.57	7.62	7.94	5.8	>5.95	
NGC 6803	7.52	11.10	8.53	8.77	8.33	8.11	—	>6.2	14
NGC 6826	10.0	11.036	7.85	8.6	7.58	7.69	—	6.04	15
NGC 7009	8.9	11.04	8.5	8.76	8.19	7.78	5.5	6.4	16
NGC 7026	10.2	11.046	8.51	8.43	7.44	7.80	>4.74	6.55	(3)
NGC 7662	10.5	11.00	8.17	8.51	7.74	7.4	5.5	6.3	(17)

We adopt $\log N(\text{H}) = 12.00$ throughout.

- (1) Model I, Aller et al. (1972)
- (2) Model II, Aller et al. (1972)
- (3) Czyzak and Aller (1970)
- (4) Aller and Czyzak (1970)
- (5) Buerger (1973)
- (6) Kaler et al. (1968)
- (7) Czyzak et al. (1975)
- (8) Aller et al. (1970)
- (9) Oliver and Aller (1969)
- (10) Aller et al. (1973)
- (11) Czyzak et al. (1968), Boeshaar et al. (1974)
- (12) Aller et al. (1969)
- (13) Czyzak and Aller (1973)
- (14) Lee et al. (1974); the helium line intensities are due to Peimbert and Torres-Peimbert (1971)
- (15) Czyzak et al. (1971)
- (16) Aller and Epps (1975)
- (17) Aller and Czyzak (1973)

bers is difficult to specify since we do not yet really know how well the extrapolation procedures work for the relevant nebulae. Nevertheless, the enhanced nitrogen abundance suggested by the Peimberts ap-

pears to be substantiated.

In a paper presented at the 1975 San Diego meeting, Czyzak and I tried to correlate chemical compositions with the spectra of the central stars, grouping them according to whether they had Wolf-Rayet type spectra, showed hydrogen and helium absorption lines, or displayed continuous spectra (see Table III). Central stars with hydrogen-rich atmospheres might be expected to have suffered less evolutionary perturbations than Wolf-Rayet type stars. For those objects so far analyzed, we find a considerable scatter in each group, but nitrogen *does* appear to be more abundant in nebulae with Wolf-Rayet nuclei. Often nebulae with Wolf-Rayet nuclei show a pronounced filamentary structure and such objects often show enhanced $[\text{N II}]$ line intensities. Planetary nebulae with continuous spectra appear to be associated more often with nebulae with "enriched" compositions.

The possibility of abundance variations with distance from the galactic center has been discussed by

TABLE III
RELATION OF CHEMICAL COMPOSITIONS OF PLANETARY
NEBULAE WITH CENTRAL STAR TYPES

RELATION OF CHEMICAL COMPOSITIONS OF PLANETARY NEBULAE WITH CENTRAL STAR TYPES			
$\log N(\text{el})/N(\text{H}) + 12.00$			
	CONTINUOUS SPECTRA	STARS WITH ABSORPTION LINES O and Of	WOLF RAYET TYPE
He	11.04	11.05	11.01
N	8.4	7.38	8.21
O	8.70	8.44	8.63
Ne	8.08	7.66	7.90
S	7.76	7.47	7.45
Cl	5.5	> 4.8	5.5
Ar	6.3	6.13	6.35

A compilation of results presented by Czyzak and Aller at the San Diego meeting of the American Astronomical Society.

d'Odorico, Peimbert, and Sabbadin (1976) who conclude that there are pronounced declines in the He, N, and O abundances with increasing distance from the galactic center. We find less marked results (see Figs. 5, 6, and 7).

Consider first the helium data. A few objects (in addition to those listed in Table II) for which detailed abundance analyses have not been completed are included. The ionic concentrations have been calculated with the concise equations given by the Peimberts, which in turn are based on theoretical calculations by Brocklehurst. The relevant line intensities of $\lambda 4471$, $\lambda 5876$, $\lambda 6678$, and $\lambda 4686$ were measured (with very few exceptions) by photoelectric photometry or with the ITS. Most of the nebulae scatter around 0.10 or 0.11. Three nebulae show considerable excesses of helium: NGC 6445 (Aller et al. 1973), NGC 6302 (Oliver and Aller 1969; Danziger, Frogel, and Persson 1973), and 86 - 8°1 (Kaler 1974a). These same objects show no detectable central stars, but have lines of N II suggestive of filamentary structure. It did not prove possible to obtain a convincing chemical composition for 86 - 8°1 by the usual extrapolation procedures; the excitation of this nebula is much too high. Our data are consistent with a slight decline of $n(\text{He})/n(\text{H})$ with R .

Figures 6 and 7 give results for O, N, S, Ne, and Ar. The chlorine data are too sketchy; they require too large extrapolation factors and have not been plotted. For NGC 6720 we give the mean abundance found from Table I (excluding neon in region no. 10). For NGC 40, results for two models are given in order to illustrate uncertainties involved for an extremely low

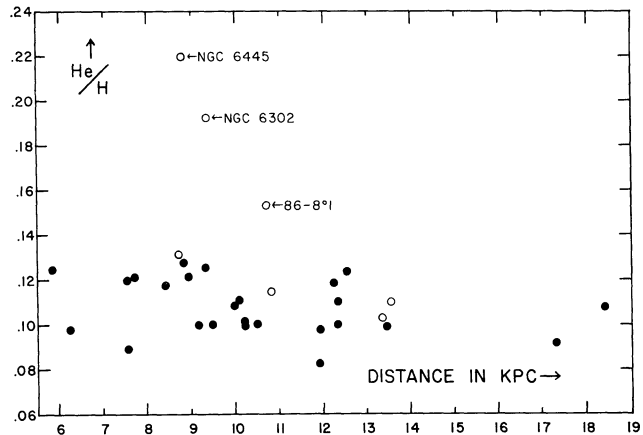


FIG. 5—Variation of the helium abundance with distance from the galactic center. The solid points refer to heliocentric distances adopted from Cudworth (1974) and converted to galactocentric distances on the assumption that the galactic center is at 10 kpc. The open circles refer to nebulae whose distances are adopted from other sources, mostly Milne and Aller (1975).

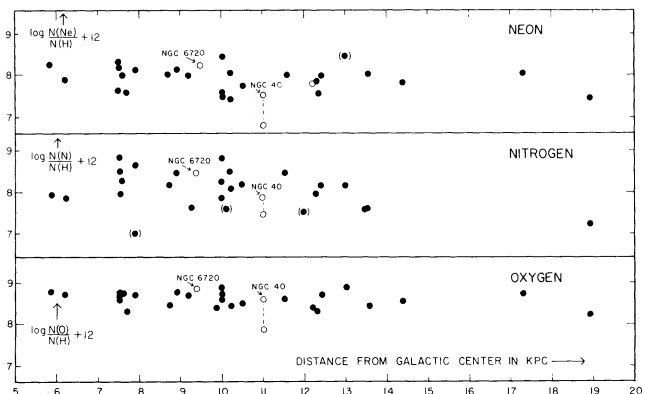


FIG. 6—The variation of the abundances of oxygen, nitrogen, and neon with distance from the galactic center. Determinations deemed rather uncertain are indicated in parenthesis. In particular, the nitrogen result for IC 4593 is very uncertain. For NGC 40, two different models have been assumed.

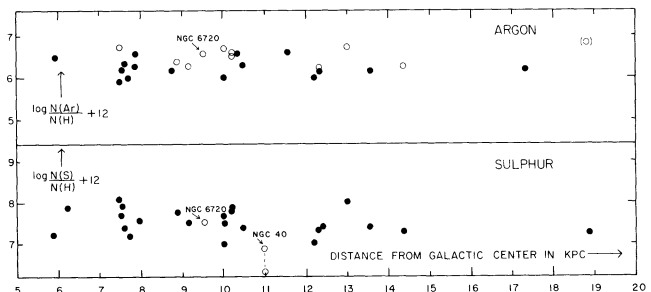


FIG. 7—The variation of the abundances of sulphur and argon with distance from the galactic center. Sulphur required corrections comparable to those employed for nitrogen even when both $[\text{S II}]$ and $[\text{S III}]$ are observed. The open circles for argon refer to those objects where the determinations should be more reliable, insofar as ionization corrections are concerned. The value for J320 at 18.9 kpc seems rather large.

excitation nebula (Aller et al. 1972). The lower abundances seem less plausible. For IC 4593, conventional procedures give an unlikely low nitrogen abundance and even the value obtained from Mrs. Buerger's model nebula seems too small. Note that the distant planetary J320 at 18.9 kpc tends to give lower abundances except for helium and argon.

There appears to be no clear-cut evidence for a variation of the oxygen abundance with R . The scatter of the individual points is rather small, largely because the correction for unobserved ionization stages is relatively unimportant, except in high-excitation objects. Nitrogen shows considerable scatter, much of which must arise from inadequate corrections for unobservable ionization stages. We did not observe $[\text{N II}]$ at all in IC 351; the point corresponding to this nebula at 16.5 kpc would fall below 7.0. The nitrogen data are consistent with a modest decline in $n(\text{N})/n(\text{H})$ with R .

The neon abundance shows little dependence on R . This element is observed usually only as Ne III , but in high-excitation objects $[\text{Ne IV}]$ and $[\text{Ne V}]$ are also found. An uncertainty in the electron temperature appropriate to the Ne IV and Ne V zones can produce a very large error in the derived abundance. Values obtained for moderate- to low-excitation objects would appear to be more reliable.

The sulfur abundance is derived from lines of $[\text{S II}]$ and $[\text{S III}]$. In principle, nebular and transauroral $[\text{S II}]$ transitions permit one to obtain both the electron density and temperature, but uncertainties in the theoretical collisional cross sections introduce error. We observe only the auroral $[\text{S III}]$ $\lambda 6312$ line; hence a calculation of the corresponding $[\text{S III}]$ concentration is sensitive to the assumed electron temperature. Finally, an extrapolation to the total sulfur abundance is subject to errors comparable to those found for nitrogen.

Argon is always represented by the $[\text{Ar III}]$ $\lambda 7135$ line, and in higher excitation objects by $[\text{Ar IV}]$ and $[\text{Ar V}]$. Extrapolations are necessarily uncertain. Open circles indicate what are considered to be the best values. Neither the argon nor sulfur abundances depend strongly on R .

Measurement of the iron abundance would be of great interest in assessing the character of the interstellar medium from which planetary nebulae formed. Shields (1975) suggested that the iron abundance in NGC 7027 was depleted below the solar value by more than an order of magnitude, whereas lighter elements appeared "normal". He proposed that the iron may be condensed onto grains as in the interstellar medium. Osterbrock (1974a), however, found no evidence for dust extinction within NGC 7027 itself; the heated dust seems to lie outside the region responsible

for the optical spectrum. There is no convincing evidence for large amounts of dust in many of the objects where we have observed lines of $[\text{Fe III}]$, $[\text{Fe V}]$, $[\text{Fe VI}]$, and even $[\text{Fe VII}]$. It is possible that in many planetaries, iron may have an intrinsically low abundance, even though O, Ne, S, Ar, etc., may have essentially "normal" (i.e., solar) abundances, but actual iron abundances cannot be calculated until we have the required atomic parameters, especially collisional cross sections.

Planetary Nebulae in External Galaxies

The most exciting advances pertain to detection and measurement of planetaries in external galaxies. From photoelectric spectrophotometry of three planetaries in each of the Magellanic Clouds, Osmer (1976) found that although the N/O ratios were similar to those found in galactic planetaries, the SMC (Small Magellanic Cloud) planetaries showed a deficiency of a factor of 10 in the oxygen abundance. The H II regions in the SMC show a similar deficiency (Aller et al. 1974; Dufour 1975; Peimbert and Torres-Piembert 1976). Most surprising of all was a 40% overabundance of helium in five of the six planetary nebulae in the Magellanic Clouds. On the other hand, Ms. Webster (1976) found helium abundances to be the same in Magellanic Cloud planetaries as in galactic bulge planetaries, while the oxygen abundance appeared to be depressed by a factor of two or three in the Magellanic Clouds as compared to the galactic bulge.

By an audacious combination of observational techniques involving narrow bandpass filters and the ITS, H. C. Ford and his associates. (Ford et al. 1973; Ford and Jenner 1975) were able to identify numerous planetaries in the companions to M31 (viz., M32, NGC 205, NGC 185, and NGC 147) and to observe the spectra and measure radial velocities for a number of them. The brightest planetaries had magnitudes of about 20; the faint $\lambda 4363$ and $\lambda 5876$ lines required for temperature and helium abundance determinations, respectively, correspond to a magnitude of 25!

The objective of this program was to assess the old population in the local group of galaxies. Unlike the planetaries in the clouds, those in local group ellipticals come from stars of the same mass. From the planetaries, one can obtain the abundances of the light elements, He, N, and O and estimate the rate at which mass is returned to the interstellar medium. From the Doppler shifts of the nebular lines, the velocity dispersion in the halo can be found. One can apply the virial theorem to determine then the masses of these elliptical galaxies. Further, by comparing the velocity dispersion in the halo and in the nucleus, one can test dynamical models of galaxies. Hence, planetary nebulae emerge as powerful tools for studies of

structure of galaxies.

From the eleven planetaries whose velocities showed them to belong to M32, Ford and his associates found a velocity dispersion of 35 km sec^{-1} , from which they deduced a mass of 4.3×10^8 solar masses by the virial theorem and a mass/luminosity ratio of 2.3. They estimated that there were 34 nebulae within 2.3 magnitudes of the brightest one. They obtained a lower limit to the mass loss of 5×10^{-4} solar masses per year. In 10^{10} years, a mass of 6×10^6 solar masses would accumulate, which is much larger than the upper limit of 10^4 solar masses estimated from radio-frequency observations and the absence of detectable optical emission. A wind may flow the material out of the galaxy.

NGC 147 is the least massive of the local group dwarf ellipticals. The globular clusters and planetary nebulae are fainter than in the other three ellipticals. NGC 147 does not seem to be bound gravitationally to its neighbor, NGC 185. The brightest planetary in NGC 185 seems to resemble an SMC object observed by Osmer in that it has a He/H ratio of 0.18 and a high electron temperature. The oxygen abundance seems depleted by a factor of 10. The planetary nebulae in M32 differ systematically in chemical composition from those in NGC 185 and NGC 205. The high excitation nebulae in M32 have strong [N II] lines comparable to H α . Although part of this difference must come from blobs and filaments, to some extent the differences must represent actual chemical composition effects. This impressive achievement of Ford and his team (Ford, Jacoby, and Jenner 1976) constitutes one of the major contributions that planetary nebulae can make to the broader problems in astrophysics and the structure of galaxies.

Concluding Remarks

As for the planetaries themselves, much observational and theoretical work remains to be done to understand their structural characteristics. Aperture synthesis techniques in radio astronomy permit construction of intensity contour maps freed from effects of dust extinction (Terzian, Balick, and Bignell 1974; Willis, George, and Kaftim-Kassim 1974). Infrared measurements (e.g., Cohen and Barlow 1974) supply information on reradiation by dust grains. Theoretical studies of the evolution of dusty model planetary nebulae (Ferch and Salpeter 1975) suggest that actual masses of ejected shells may lie closer to 0.5 solar mass than to the usually assumed value of 0.1 or 0.2. Most likely, a range of masses exists—from less than 0.10 to perhaps 0.5 or more. Selection effects would work in favor of the more massive shells.

Partly inspired by the phenomenon of FG Sagittae, attention has been drawn to multiple shells (e.g.,

Kaler 1974b). Wentzel (1976) demonstrated the complexities attendant upon multiple shell ejection. He suggested that some of the thin shells of ionized gas observed around planetaries may be consequences of double shell ejection in the course of the evolution of the central star.

Ultraviolet observations such as those by Bohlin, Marionni, and Stecher (1975) of NGC 7027 suggest tantalizing new opportunities, a chance to observe diagnostic lines of great importance, and to determine abundances of elements such as carbon. In this brief space it has not been possible to do justice to our topic. The reader is referred to excellent recent reviews by Miller (1974) and by Osterbrock (1974b).

Special thanks are due to my colleague, Dr. Holland Ford, for supplying me with results of his work on planetary nebulae in advance of publication. The abundance results quoted herein (Tables I, II, and III) constitute a preview of a joint program carried out in collaboration with Professor Stanley Czyzak, the details of which are being published elsewhere. The UCLA stellar- and nebular-abundance program is supported in part by NSF grant AST 71-03362 AO4 to the University of California, Los Angeles. Grateful acknowledgment is made to the Campus Computing Network, and to Mr. C. D. Keyes who has rendered indispensable service in the ITS data reduction.

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Note added in proof:

Since the preceding was written, T. Barker presented results at the Haverford meeting of the American Astronomical Society (*Bull. A.A.S.* **8**, 371, 1976) which show little, if any, dependence of planetary nebula chemical composition on distance from the galactic center.