THE CHEMICAL COMPOSITION OF PLANETARY NEBULAE

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The problem of the determination of the chemical compositions of planetary and other gaseous nebulae constitutes one of the most exasperating problems in astrophysics. On the one hand, the problem appears to be conceptually simple – the mechanisms of excitation of the various lines appear to be well understood and the necessary physical parameters can be obtained by quantum mechanical theory. Yet the task is a difficult one and we want to explore some of the significant features.

Three distinct problems are involved:

(1) *Basic physical parameters and excitation theory.* These include the transition probabilities for forbidden lines, and collision strengths, not only for the forbidden lines but also for transitions from low levels that are necessarily metastable – as e.g. in Mg I. Particularly urgently needed – not just for planetaries, but also for objects such as η Carinae, novae, and combination variables – are collision strengths for iron atoms in various stages of ionization. Ubiquitous iron shows up, in one form or another, in almost every celestial source.

Also needed are appropriate theories for numerous weak permitted lines that appear in a number of nebulae. For example, carbon is represented only by permitted lines of C II, C III, and C IV. Some work on this element is being done by Clarke. Most nitrogen ions in planetaries are revealed only by permitted lines. Both these elements – so important in hydrogen-burning processes in stars – need our urgent attention. Seaton has suggested that the permitted lines of oxygen formerly attributed to recombination actually are excited by the central star. Hence, they cannot be used to obtain ionic abundances. Therefore it would be worthwhile to study the permitted lines of O II and Ne II, since the ionic concentrations of O^{++} and Ne^{++} can be obtained from their forbidden lines; thus a check on the theory is possible, and for these ions at least it would be possible to assess the relative importance of direct line excitation and recombination.

(2) *Adequate observational data on a good representative set of nebulae.* In practice, we are pretty well limited to nebulae of high or moderately high surface brightness. We need to know the integrated brightness of the nebula in its strongest lines in absolute units. These data are best obtained by photoelectric photometry. We also need the relative intensities of the weaker lines and of the nebular continuum over as long a wavelength range as possible. Radio-frequency data help us to assess space

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absorption, and we hope that ultimately observations from above the Earth's atmosphere will enable us to fill in the blank places in the spectrum.

(3) We must make allowance for the *structural features and stratification effects* in nebulae and for the *distribution of atoms among various stages of ionization*. The first of these effects can sometimes be handled if we can obtain nebular spectra on a sufficient scale, with the slit of the spectrograph placed in a known position in the object. Examples will be described shortly.

The classical investigations of Bowen and Wyse (1939) and of Wyse (1942) constituted the first definitive study of the chemical compositions of the planetaries. Looking back, after nearly a generation, one is impressed by their observational skill and the enduring character of their essential conclusions. Theoretical studies by Menzel and his associates enable certain refinements to be introduced, but the problem of collision strengths remained as a roadblock until it was successfully resolved by Seaton (1953) and his associates and others who followed the trail he blazed. See Czyzak (1967), Czyzak and Krueger (1967), and Seraph *et al.* (1966).

Using the notation of Seaton (1960) and the equations of statistical equilibrium (Menzel *et al.*, 1941; Aller, 1956, p. 192) and modern cross-section data reviewed here recently by Seaton, we may write down some typical equations. In each instance, we express the concentration of the ion in terms of that of the O^{++} ion, and the intensities of the relevant forbidden lines in terms of the sum of the intensities of the green nebular lines.

We define $x = 0{\cdot}01\, N/\sqrt{T}$, so that $x = 1$ for a 'standard' bright nebula with $N = 10000$ cm^{-3} and $T = 10000$ °K. Let I_n denote the sum of the intensities of the nebular transitions of the ion in question, I_a the sum of the intensities of the auroral transitions and I_{TA} the sum of the intensities of trans-auroral transitions. Let I_0 denote the sum of the intensities of the green nebular lines. Let $D(y) = 10^y$. We assume that the ionic and [O III] lines are produced in the same layers, so that the same values of x and T_ε are applicable.

Nitrogen:

$$\frac{N(\mathrm{N}^+)}{N(\mathrm{O}^{++})} = 0{\cdot}149\, \frac{3770\left(\frac{1}{x}+0{\cdot}14\right)}{1+0{\cdot}29x}\, \frac{D\left(\frac{7800}{T}\right)}{1+67/x}\, \frac{I_a(\mathrm{N\,II})}{I_0}$$

$$\frac{I_{\mathrm{neb}}}{I_a} = \frac{8{\cdot}5D(10\,800/T)}{1+0{\cdot}29\,x} \qquad [\mathrm{N\,II}]$$

Oxygen:

$$\frac{I_0}{I(\lambda 4363)} = \frac{7{\cdot}15}{1+0{\cdot}028x}\, D\left(\frac{14\,300}{T}\right) \qquad [\mathrm{O\,III}]$$

New fluorine cross-section data yield:

$$\frac{N(\mathrm{F}^{+3})}{N(\mathrm{O}^{++})} \sim 1{\cdot}0\, \frac{I_{\mathrm{neb}}(\mathrm{F\,IV})}{I_0}\, D(2980/T) \qquad [\mathrm{F\,IV}]$$

For the ions of neon we have the following relation:

$$\frac{N(\mathrm{Ne}^{++})}{N(\mathrm{O}^{++})} = 0\cdot 0983\,\frac{(1+1020/x)}{(1+67/x)}\,D\left(\frac{3480}{T}\right)\frac{I_n(\mathrm{Ne\,III})}{I_0} \qquad [\mathrm{Ne\,III}]$$

$$\frac{N(\mathrm{Ne}^{+4})}{N(\mathrm{O}^{++})} = 0.0365\,\frac{(1+2190/x)}{(1+67/x)}\,D\left(\frac{6100}{T}\right)\frac{I_n(\mathrm{Ne\,V})}{I_0}\,, \qquad [\mathrm{Ne\,V}]$$

while at low densities ($x \leqslant 1\cdot 0$)

$$\frac{N(\mathrm{Ne}^{+3})}{N(\mathrm{O}^{++})} \simeq 9\cdot 8\,\frac{I_a(\lambda 4724{,}5)}{I_0}\,D\left\{\frac{26\,400}{T}\right\} \qquad [\mathrm{Ne\,IV}]$$

The only ion of sodium observed is Na^{+++}; we have

$$\frac{N(\mathrm{Na}^{+3})}{N(\mathrm{O}^{++})} = 0\cdot 020\,\frac{(1+4510/x)}{(1+67/x)}\,D\left\{\frac{5800}{T}\right\}\frac{I_n(\mathrm{Na\,IV})}{I_0} \qquad [\mathrm{Na\,IV}]$$

Singly ionized sulphur presents a difficult problem because of collisional interlocking between levels of the same term. The most elementary approach is to ignore the fine structure and assume that collisions distribute the ions between levels in proportion to their statistical weights.

For 10000 °K $< T <$ 20000 °K and $0\cdot 2 < x < 10$, the factor expressing deviation from thermodynamic equilibrium can be put in the form $(b_3/b_1) = 2\cdot 6 \times 10^{-4}x$.

Then, from the trans-auroral lines

$$\frac{N(\mathrm{S}^{+})}{N(\mathrm{O}^{++})} = \frac{48}{x+67}\,D\left(\frac{2820}{T}\right)\frac{I_{\mathrm{TA}}(\mathrm{S\,II})}{I_0} \qquad [\mathrm{S\,II}]$$

The red nebular and violet trans-auroral lines are sensitive to both temperature and density:

$$\frac{I_{\mathrm{TA}}(\mathrm{S}^{+})}{I_{\mathrm{neb}}(\mathrm{S}^{+})} = 0\cdot 164\left\{3\cdot 8 + x\left[1 + 1\cdot 32\,D\left(-\frac{6000}{T}\right)\right]\right\}D\left(-\frac{6000}{T}\right) \qquad [\mathrm{S\,II}]$$

For the [S III] lines we have the following relationships:

$$\frac{N(\mathrm{S}^{++})}{N(\mathrm{O}^{++})} = 0\cdot 60\left[\frac{1+101/x}{1+67/x}\right]D\left(-\frac{5800}{T}\right)\frac{I_n(\mathrm{S\,III})}{I_0}$$

$$\frac{N(\mathrm{S}^{++})}{N(\mathrm{O}^{++})} = 0\cdot 070\left(\frac{1+\dfrac{3700}{x}}{1+67/x}\right)D\left(\frac{4320}{T}\right)\frac{I_a(\mathrm{S\,III})}{I_0}\,. \qquad [\mathrm{S\,III}]$$

An expression similar to the last holds for the trans-auroral line near the Balmer limit, λ3722, except that the constant 0·070 is replaced by 0·124.

The [Cl III] λ5517/5537 line ratio should be a sensitive indicator of the density, but it will be necessary to compute the collision strengths for $^2D_{3/2}$–$^2D_{5/2}$ and $^2P_{1/2}$–$^2P_{3/2}$ exchanges. Similar remarks apply to [Ar IV]. The [Cl III] λ5517 line intensity is related to the concentration of Cl^{++} ions by:

$$\frac{N(\mathrm{Cl}^{++})}{N(\mathrm{O}^{++})} = \frac{11{\cdot}5D\left(\dfrac{-1220}{T}\right)}{1+\dfrac{67}{x}} \left\{\frac{1+\dfrac{3{\cdot}63}{x}+1{\cdot}7D\left(\dfrac{-7300}{T}\right)}{1+0{\cdot}193D(-7300/T)}\right\} \frac{I(5517)}{I_0} \qquad [\mathrm{Cl\,III}]$$

with an analogous expression for $I(5537)$.

Ions of Cl^{+++} are represented by lines in the green (auroral transition) and near infrared

$$\frac{N(\mathrm{Cl}^{+++})}{N(\mathrm{O}^{++})} \simeq 19D\left(\frac{-4250}{T}\right) I_n\frac{(\mathrm{Cl\,IV})}{I_0} \qquad [\mathrm{Cl\,IV}]$$

$$\frac{N(\mathrm{Cl}^{+++})}{N(\mathrm{O}^{++})} \simeq 14{\cdot}2D\left(\frac{7300}{T}\right)\frac{I_a(\mathrm{Cl\,IV})}{I_0}.$$

Argon is represented by forbidden lines of [Ar III], [Ar IV] and [Ar V]. We have

$$\frac{N(\mathrm{Ar}^{++})}{N(\mathrm{O}^{++})} \sim 79D\left(\frac{8050}{T}\right)\frac{I(\lambda 5191)}{I_0} \qquad \text{auroral line } [\mathrm{Ar\,III}]$$

$$\frac{I_a(\mathrm{Ar}^{++})}{I_n(\mathrm{Ar}^{++})} \simeq 0{\cdot}091D\left(\frac{-12\,000}{T}\right). \qquad \text{ratio of auroral and nebular lines}$$

The most frequently observed line of [Ar IV] is λ4740; $^2D_{3/2}$–$^4S_{3/2}$ its companion λ4711 is often blended with He I λ4713:

$$\frac{N(\mathrm{Ar}^{+++})}{N(\mathrm{O}^{++})} = \frac{0{\cdot}520}{1+67/x} D\left(\frac{705}{T}\right) \left\{\frac{1+\dfrac{229}{x}+2{\cdot}8D\left(\dfrac{-8660}{T}\right)}{1+0{\cdot}214D(-8660/T)}\right\} \frac{I(4740)}{I_0}.$$

The red auroral transitions of [Ar IV] are often observed, although less conveniently since they fall in the λ6700 region.

For the [Ar V] lines we may write

$$\frac{N(\mathrm{Ar}^{+4})}{N(\mathrm{O}^{++})} \simeq 2{\cdot}71D\left(\frac{-3180}{T}\right)\frac{I_n(\mathrm{Ar\,V})}{I_0}, \quad \frac{N(\mathrm{Ar}^{+4})}{N(\mathrm{O}^{++})} \sim 41{\cdot}0D\left(\frac{10\,400}{T}\right)\frac{I_a(\mathrm{Ar\,V})}{I_0}.$$

Potassium is represented by lines of [K IV], [K V], and [K VI]. Thus

$$\frac{N(\mathrm{K}^{+3})}{N(\mathrm{O}^{++})} \simeq 26{\cdot}2D\left(\frac{11\,300}{T}\right)\frac{I_a(\mathrm{K\,IV})}{I_0}, \quad \frac{N(\mathrm{K}^{+3})}{N(\mathrm{O}^{++})} = 1{\cdot}54D\left(\frac{-2570}{T}\right)\frac{I_{\mathrm{neb}}(\mathrm{K\,IV})}{I_0}$$

$$\frac{N(\mathrm{K}^{+4})}{N(\mathrm{O}^{++})} \sim 1{\cdot}04D\left(\frac{2420}{T}\right)\frac{I_{\mathrm{neb}}(\mathrm{K\,V})}{I_0}, \quad \frac{N(\mathrm{K}^{+5})}{N(\mathrm{O}^{++})} = 3{\cdot}6D\left(\frac{-2120}{T}\right)\frac{I_{\mathrm{neb}}(\mathrm{K\,VI})}{I_0}.$$

The [Ca V] λ5309 transition is sometimes observed:

$$\frac{N(\mathrm{Ca}^{+4})}{N(\mathrm{O}^{++})} \simeq 28D\left(-\frac{1360}{T}\right)\frac{I_{\mathrm{neb}}(\mathrm{Ca\,V})}{I_0}.$$

The lines of potassium, calcium, and sodium appear in nebulae whose ionization level is appropriate. They yield abundances comparable with values expected for stars.

Before considering applications of these equations to specific nebulae, we must discuss the observational problems involved.

1. Observational Data; Requirements and Limitations

In the 'thirties when the theory of spectrum-line excitation in gaseous nebulae began to be developed in quantitative form, it became evident that very severe requirements would be placed on the observations. Inference of physical conditions in a nebula demands accurate line-intensity ratios, sometimes over large wavelength intervals. Often the critical spectral lines are very weak. Photoelectric photometry, which is indispensable for the stronger lines, is of limited usefulness for weak lines in a crowded region of the spectrum or for lines such as 3965 (He I), 3969 [Ne III] and 3970 Hg. In practice, one combines photoelectric and photographic spectrophotometry. The photoelectric scanner gives the integrated brightness of the nebula in the strongest lines and permits measurements of a few weaker ones if one has the patience and above all the telescope time. The calibrated photographic plate enables one to achieve both angular and spectral resolution.

Clearly, one would like to observe over as broad a spectral range as possible. The λ3000 – λ5000 region of the spectrum presents no particular difficulties with fast emulsions and modern nebular spectrographs. The region λ5000 – λ5900 can be handled nicely with an image converter and the λ6000 – λ6700 region again with red sensitive plates. From λ6700 to about λ9000 the hypersensitized photographic plate can be used, but in the infrared we can reach only the strongest line with appropriate photocells.

It has become increasingly evident that we also need angular scale; for some problems one must go to the Coudé focus of a large telescope to obtain carefully guided spectrograms.

One must mention the photometric difficulties inherent in measuring line intensities over a range of as much as 30000 (as e.g. in NGC 7662) and over a spectral range from 3000 Å to 10000 Å. The problem is exacerbated by intrinsic changes in intensity over short angular distances in the nebula.

The results reported here were obtained mainly at the Lick and Mount Wilson Observatories. Recently, we have collaborated with Kaler, who has obtained spectrophotometric observations at Kitt Peak. At Mount Wilson we have emphasized relatively high-dispersion Coudé spectroscopy of bright planetaries and photoelectric spectrophotometry with the Cassegrain scanner at the 60-inch. The effort at Lick Observatory has been centered on the nebular spectrograph at the prime focus of the 120-inch reflector, insofar as the blue spectral region is concerned. Thanks to Walker, who has promoted the use of the Lallemand electronic camera at the Coudé focus of the 120-inch, we now have data on the green-yellow region $\lambda 4700$ – $\lambda 5900$ in a number of bright planetaries.

Chopinet (1963) has pioneered in spectrophotometry of nebulae with an electronic camera. With suitable choice of developer and emulsion, and with due care in observing an appropriate comparison star, it is possible to attain an accuracy comparable with that obtained by good photographic photometry (Walker, 1963; Walker and Aller, 1965). Since photographic emulsions are notoriously slow in the region near $\lambda 5200$, the gain in speed offered by the image converter is well worth the extra effort involved.

The region longward of $\lambda 5900$ remains inadequately covered even for the brighter planetaries; there are many important lines in this region.

It will be of enormous importance to obtain observations from outside the Earth's atmosphere both in the infrared and in the heretofore inaccessible ultraviolet. Only a few planetaries are bright enough to be observed in this way even when space telescopes are fully operative (cf. Code, 1960; Aller, 1961; Osterbrock, 1963, 1967; Gould, 1966).

2. Effects of Stratification and Filamentary Structure

Analyses of planetary nebulae are complicated by effects of stratification – i.e. the concentration of more highly ionized atoms toward the center (cf. Bowen, 1928) and the tendency for the nebular gas to exhibit considerable structure (Minkowski, 1964).

Let us examine, first of all, some of the stratification effects as exhibited in the blue region of the spectrum. Figure 1 (upper) shows spectra of NGC 6778, IC 5217, J 900, NGC 6818, and NGC 6741 obtained with the Lick 120-inch with the prime-focus nebular spectrograph. The spectra of NGC 6741 and IC 5217 have been widened because these nebulae are very small. Pronounced stratification effects are evident in NGC 6818 and NGC 6778, both of which have faint central stars that appear to have a nearly purely continuous spectrum. In NGC 6818 the [Fe v] radiation seems strongly confined to the central region even though [Ne v] is spread throughout the nebula.

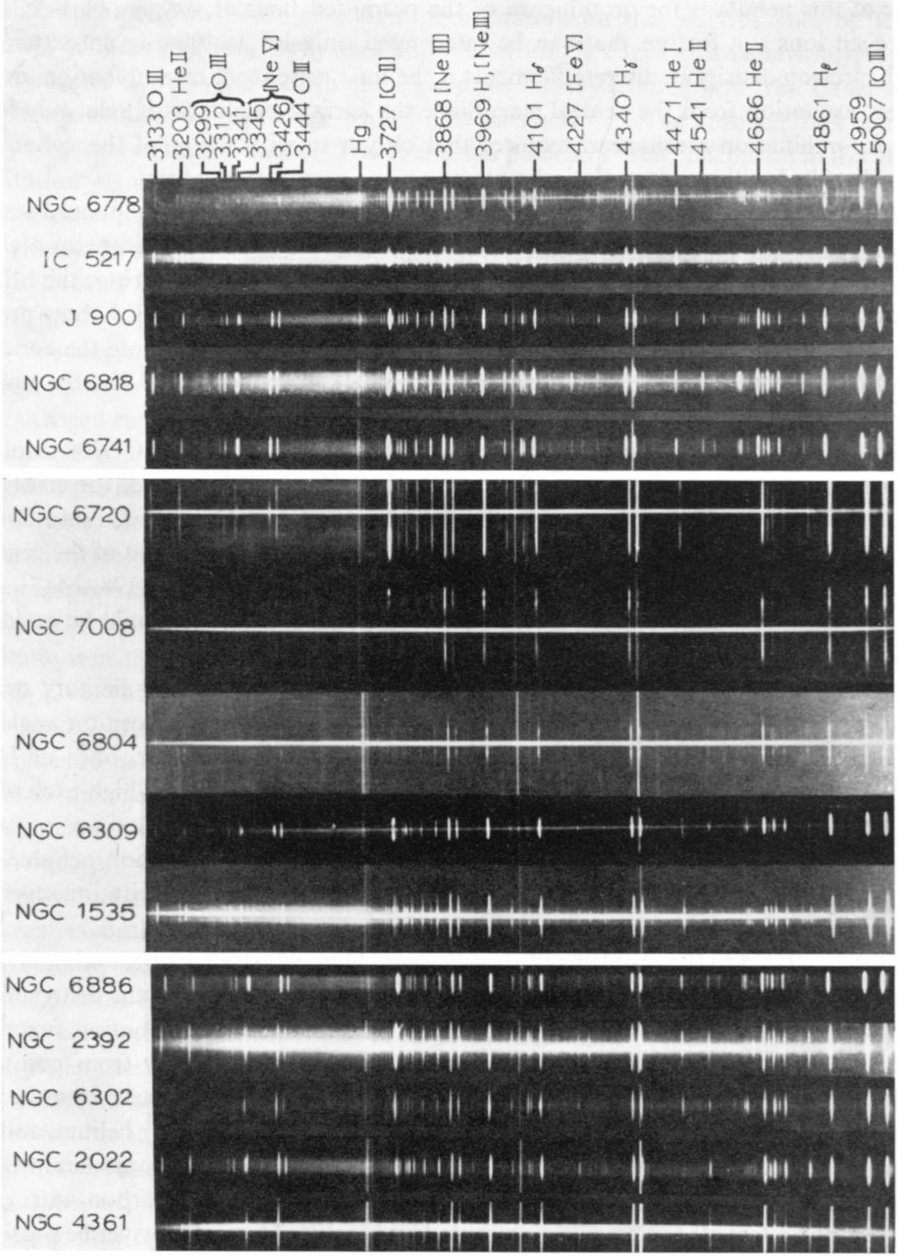

FIG. 1. *Spectra of planetary nebulae in the blue spectral region, taken with Lick Observatory prime-focus nebular spectrograph.*

Pronounced stratification effects in NGC 6778 are evident. An outstanding characteristic of this nebula is the prominence of the permitted lines of oxygen, carbon, and nitrogen ions – a feature that can be interpreted only by postulating an extremely high electron density in discrete filaments if the lines arise from recombination, or by direct excitation from the central star. Since the surface brightness is relatively low, the recombination mechanism requires that only a small fraction of the volume is actually filled with dense radiating matter.

The middle part of Figure 1 shows results for five nebulae with pronounced stratification effects. NGC 1535 is a classical two-ringed planetary of Vorontsov-Velyaminov's type IV. The spectrograph slit was placed through the bright ring; the bright streak is light scattered from the central star. NGC 1535 and NGC 6309 show pretty much the classical pattern of stratification as proposed by Bowen. Note the concentration of [Ne v] and 4541 He II towards the central star in NGC 6309 and the prominence of He I and 3727 [O II] in the outer layers.

The other three objects are of relatively low surface brightness. NGC 6804 displays a somewhat dim ring of rather uniform excitation. On the other hand, the centre of the ring in NGC 6720 is occupied by ions of high excitation (Minkowski and Osterbrock, 1960). Note especially the [Ne v] radiation which hugs the region of the central star. In the outer ring [S II] is enhanced as are also λ3727 [O II], He I λ3178, λ4471 and Mg I λ4571. Were it not for its low surface brightness, NGC 6720 would be an ideal object for a study of stratification effects.

NGC 7008 shows effects of both pronounced stratification and filamentary structure. The slit of the 120-inch nebular spectrograph was placed at a position angle of 25°. In the high-excitation blob, which is closer to the central star, lines of He II λ4686, [Ar IV], and O III are observed, whereas in the outer blob, the high-excitation lines are missing.

The bottom part of Figure 1 shows a number of very high-excitation nebulae, of which NGC 4361 is probably the most highly excited. Atmospheric excitation severely weakens the ultraviolet spectrum of NGC 4361.

Closely related to the problems of stratification, filamentary structure, and point-to-point excitation differences within gaseous nebulae is the question of the distribution of atoms among various stages of ionization. The ionization–distribution function introduced by Bowen and Wyse (1939) must fluctuate considerably from point to point in certain nebulae. The best way to solve this problem would be to observe the ions of each element in several stages of ionization. This is possible for helium, and to some extent for other elements such as neon, carbon, nitrogen, and potassium. Many elements are represented only by one or two ionization stages. For carbon, nitrogen, oxygen, and a few other elements represented by permitted lines it may yet be possible to separate the relative contributions of direct stellar excitation and recombination theories.

Some nebulae certainly contain condensations of greatly varying excitation and density. Suppose we take a series of nebulae of moderate to high surface brightness and arrange them in order of increasing excitation on the basis of lines of He II, [Ne V], etc. The [N I] and [N II] lines show a strikingly capricious behaviour (Wyse, 1942) which is well-exhibited in the Lick observations secured with the Lallemand electronic camera, as applied by Walker and his associates. The nitrogen lines tend to vary together. In the moderately low-excitation planetary NGC 6826, and in the high-excitation planetaries NGC 6818 and NGC 6826, the nitrogen lines are very weak. On the other hand they are strong in the Orion Nebula, in the low-excitation planetary IC 418 and in the high-excitation planetaries NGC 6741, Anon 21^h31^m and especially NGC 2440. Particularly marked is their great strength in the remarkable nebula NGC 6302.

Is this behaviour of the nitrogen lines an abundance effect or an excitation effect? We may answer this question partially at least by examining the spatial distribution of the nitrogen radiations within a given nebula (Walker and Aller, 1967).

In NGC 6720 the radiations of [Cl III], [N I], [N II], and He I all tend to be concentrated in the outer ring, while, as previously noted, He II, [Ne V], etc. are found in the inner parts. Even in the very small planetary NGC II 2003, [N II] is concentrated differently from other elements. In NGC 6543, [N I] and [N II] are concentrated in particular condensations, while [Fe VI] λ5676 and [Fe III] show quite different distributions. This object is an example of a nebula where there seem to be quite different excitations in different filaments. In the extremely inhomogeneous, broken-ring nebula, NGC 2392, the brighter, inner ring shows prominent lines of [Cl III], [Fe III], He I, He II, and [N II] while the fainter, outer blob shows [N I] as its strongest feature. The complicated nebula NGC 2440 (cf. Minkowski, 1964) shows considerably different blobs of nitrogen and ionized helium.

We are tempted to conclude that in objects such as NGC 2440, NGC 6302 and others mentioned above, filaments of both high and low excitation are involved. In some, the individual blobs are easily seen, but in others, such as NGC 7027, the blobs of different excitation lie below the resolution limits of our instruments.

In spite of these complexities, we must still try to find out what we can about the chemical composition of planetaries. Do field planetaries show composition abnormalities comparable to those found in M 15 by O'Dell *et al.* (1964)? That is, do there exist planetaries with chemical compositions differing greatly from the average?

Some years ago, many of us were inclined to believe that all planetaries probably had about the same chemical composition, and that apparent differences arose from difficulties in allowing for stratification effects, etc. One ratio which appears to be measurable with a reasonable degree of accuracy in most planetaries is the He/H ratio, and this seems to be nearly constant from one planetary to another (Mathis, 1957; Aller, 1964; O'Dell, 1963). In some nebulae, argon and metals such as sodium or potassium are observed in 2 or 3 ionization stages. Neon is sometimes observable as [Ne III], [Ne IV], and [Ne V], so that the neon/hydrogen ratio can be estimated.

Rather than present average results from a large number of nebulae (see e.g. Aller, 1964) we will illustrate some of the difficulties involved by comparing results gotten for three nebulae with rich bright-line spectra: NGC 7072, NGC 7662 and NGC 2022.

NGC 7027 is a tempting object for analysis because it exhibits such a rich spectrum. An earlier attempt (Aller, 1956) to analyze the spectrum of this object led to the conclusion that: "The results can be understood in terms of a nebula consisting of numerous filaments, knots, and tenuous regions such that the density may range from perhaps less than 10000 ions/cm^3 to perhaps something like 200000 ions/cm^3. The probable, but not directly observable, filamentary structure of NGC 7027 thus imposes a fundamental limitation on the accuracy with which the abundances of the ions can be found in this object." These conclusions were substantiated by Seaton and Osterbrock (1957) and by a direct photograph obtained by Minkowski. The nebula does have a distinct filamentary structure. With the availability of collisional line strengths for ions of the 3p^n row, additional relationships involving nebular and auroral transitions can be utilized. These all tend to indicate that the radiations of these ions, e.g. [S II], [Ar IV], [Cl III], originate in condensations whose densities are higher than the average density inferred from the angular diameter and surface brightness of the nebula.

If an attempt is made to use an average filament and an ionization-distribution curve deduced primarily from the ions of neon, the results obtained will be somewhat as given in Table 1. Successive columns give the element, the number of ions observed compared with the number of ions of O^{++} (we tabulate this for ions represented by forbidden lines), the estimated ratio of the total number of ions to the observed number of ions, and the logarithm of the number of ions on the scale $\log N(\mathrm{H}) = 12{\cdot}00$. The column headed 'Stellar Abundance' refers to an average deduced for our corner of the galaxy from solar system and stellar data (cf. Aller, 1961, p. 192). The

Table 1

Composition of NGC 7027

Element	N/N (O^{++})	$N_{\mathrm{T}}/N_{\mathrm{obs.}}$	log N	Stellar Abundance	Neb-Star	(1956)
Hydrogen		1·0	12·00	12·00		12.00
Helium		1·0	11·23	11·21	+0·02	11·25
Nitrogen	3·1	32	8·5	8·05	+0·5	8·67
Oxygen	7·8	7·8	9·0	8·95	+0·05	8·93
Fluorine	0·0016	2·2	5·3	6·0	−0·7	5·63
Neon	1·25	1·05	8·2	8·70	−0·5	8·08
Sodium	0·002	1·86	6·4	6·30	+0·3	–
Sulphur	0·78	19·3	8·0	7·35	+0·65	8·03
Chlorine	0·061	6·5	6·9	6·25	+0·6	7·0
Argon	0·06	2·3	6·9	6·88	0·0	7·3
Potassium	0·0056	1·3	5·8	4·82	+1·0	6·1
Calcium	0·042	2·2	6·7	6·19	+0·5	6·1

next column gives the difference in the sense nebula minus star, and the last column gives the corresponding numbers deduced in 1956.

The nebula shows no stratification effects so we have assumed that the same electron temperature, $T_e = 15000$ °K, holds throughout although the density might be expected to change. We have assumed therefore that the same ionization–distribution curve holds throughout.

Glancing first at the differences between the stellar and nebular results, much of the discrepancy may represent the effects of bad estimates, but some may be real. The third column gives the factor by which the number of observed ions has been multiplied to give the total number of ions of that particular element. It is deduced from the distribution curve giving the relative number of ions in different stages of ionization; such a procedure can give only a rough estimate, but it can tell us whether or not we are observing a significant fraction of the ions of a particular element. Sulphur is observed only as [S II] and [S III], but most of the sulphur atoms must exist in more highly ionized stages. The correction factor of 19 is clearly very uncertain; it could easily be three times smaller. The largest factor is for nitrogen and here we are urgently in need of recombination rates so that we might deduce the numbers of missing ions from permitted lines of N II and N III.

Effects of filaments with differing densities and excitations are probably more serious for some ions than for others. Probably, argon, chlorine, and sulphur are the more seriously affected. In addition, further refinements are needed in the theory of collisional strengths for these ions. There is some hint that argon, potassium, and calcium may be more abundant than in a normal star, but the problem of the filaments of differing excitation and density must be solved before any such conclusions can be proclaimed.

Bowen and Wyse (1939) pointed out that the range in excitation in NGC 7662 was much smaller than in NGC 7027. In the bright ring of this nebula, at least, we are dealing with a more nearly homogeneous situation. Sulphur and nitrogen are represented only by low stages of ionization, and the vast bulk of atoms of these elements are not observable, at least by their forbidden lines. Stratification effects, which

Table 2

Abundances in NGC 7662

Element	$\frac{N\text{(total)}}{N\text{(obs.)}}$	log N	Element	$\frac{N\text{(total)}}{N\text{(obs.)}}$	log N
Hydrogen		12·00	Sodium	2·6	6·2
Helium	1·0	11.25	Sulphur	52	7·8:
Nitrogen	126	7·9	Chlorine	4·1	7·0
Oxygen	6·7	8·93	Argon	1·3	6·8
Fluorine	1·5	4·8	Potassium	1·3	5·8
Neon	1·0	8·1	Calcium	2·7	6·2

imply a possible change in electron temperature as well as ionization with distance from central star, are important in this nebula. The electron temperature deduced from the [O III] lines is in the neighbourhood of 13000 °K, but we have assumed that in the zone where the [Ne IV] lines are produced $T_e = 17000$ °K, while it rises as high as 20000 °K in the [Ne V] zone. The ionization curve, essentially based on neon, has been applied to all elements except helium. In particular, it seems unlikely that oxygen ions would show an appreciably different ionization distribution than neon. Unfortunately, large correction factors are required for nitrogen and sulphur – so the results quoted for these elements are little more than flimsy guesses. For O, Na, Cl, Ar, K the results agree reasonably well with NGC 7027. The abundances of F and Ca appear to be lower in NGC 7662.

As a third example, consider the high-excitation planetary NGC 2022. Here is a planetary for which composite estimate are difficult because of effects of high ionization. Because of its lower surface brightness, fewer lines are available and the number of observable ions is reduced. No information on the abundance of chlorine or sulphur can be deduced from available forbidden line data. The electron temperature is adopted as 17500 °K for all except the highest-excitation ions such as [Ne V], for which we adopted $T_e = 20000°$. Helium and neon appear to define a good ionization curve; the intensity of O IV λ3411 lines is consistent with a pure recombination origin. The nitrogen abundance is difficult to estimate. Argon and potassium seem to give reasonable results.

Table 3

Results for NGC 2022

Element	log N	Element	log N	Element	log N
Hydrogen	12·00	Oxygen	8·6	Argon	7·1
Helium	11·08	Nitrogen	7·9	Potassium	5·4
		Neon	7·6		

In other nebulae, such as NGC 7008 and NGC 6720 which have been studied by Seligman and Bohannan, respectively, attempts have been made to concentrate on individual knots and filaments, or particular zones of the nebula. By examining several regions of differing excitation it may be possible to put together a more definitive picture of a compositie nebula than is possible by considering an ‘average’ region or the integrated spectrum of the object.

There are some conclusions that would appear to emerge. Although the hydrogen/helium ratio seems to be nearly constant from one nebula to another – as various investigators have found, and although there do not appear offhand any confirmed examples as extreme as the M 15 nebula discussed by O’Dell, Peimbert, and Kinman (1964), there may be a number of real differences.

For the construction of models of planetary nebulae, and similar tasks where approximate abundances are needed, we propose the figures of Table 4 for rough guidelines.

Table 4

Logarithms of relative numbers of atoms

Hydrogen	12·00	Oxygen	8·9	Sodium	6·6	Argon	7·0
Helium	11·23	Fluorine	4·9	Sulphur	7·9	Potassium	5·7
Nitrogen	8·1:	Neon	7·9	Chlorine	6·9	Calcium	6·4:

Progress in this field requires the construction of detailed models of individual nebulae for which good observational data can be secured – radio-frequency measurements, isophotal contours and spectrophotometric measurements. For several nebulae the requisite information seems almost at hand.

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DISCUSSION

Flower: The weak intensity of the [N I] λ 5199 line in some nebulae is probably due to the absence of a region in which there is neutral nitrogen plus electrons.

Aller: The capricious behaviour of the [N I] and [N II] lines is interpreted as meaning that regions of very low excitation may be found in some nebulae, such as NGC 2440, but not in others, such as NGC 7662.

Reeves: The fact that the Ne/O ratio is smaller in nebulae than in stars is of great importance for nucleosynthesis. How certain are you of this result?

Aller: It is measured in B stars, and is good only to within a factor of 10.

Underhill: From my attempts to determine the Ne and O abundances in 10 Lacertae, I would reduce the ratio Ne/O by about a factor 5 from the usual 'cosmical abundance'.

Van Horn: Would you be willing to commit yourself to a general impression on the abundances? In particular, do the C and O abundances in the planetaries appear generally higher or lower than the cosmic abundances?

Aller: It is difficult to give firm numbers for the C/O ratio. The carbon abundance depends on the permitted lines of C II, C III and C IV. When a proper theory of recombination is worked out, I believe it will be possible to compare predicted and observed intensities for lines arising from levels of different excitation potential, in order to decide between recombination and stellar radiative excitation. The carbon abundances derived by our group seem rather high, but we thought this might be due to inadequacies in the recombination theory. As for O, we should compare abundances of O^{++} derived from O II recombination lines with those from the [O III] lines. So far, there is no evidence that the C/O ratio in planetaries actually differs from the local 'cosmic' abundance.

Gebbie: We have computed oxygen abundances for 38 planetary nebulae. The O^{+} and O^{+2} abundances were obtained from forbidden lines, using the O II and O III collision strengths of Seaton and his collaborators, and using observed line intensities from all available data including recent photo-

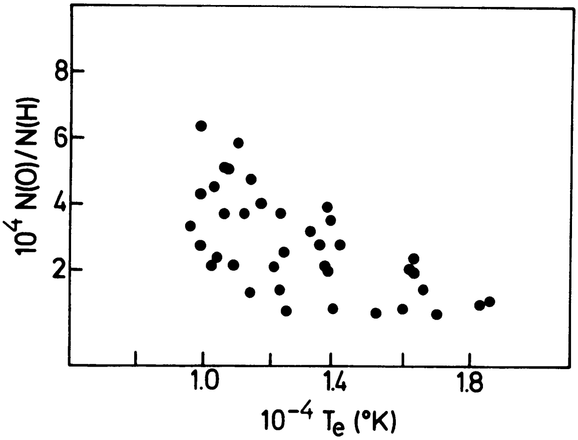

FIG. 2. *Abundances of oxygen relative to hydrogen in 38 planetary nebulae, plotted as a function of apparent electron temperature* T_e.

electric measurements of Aller and his collaborators, of O'Dell and of Vorontsov-Velyaminov and his collaborators. Allowance was made for the higher ions of oxygen by using Seaton's relation

$$\frac{N(\mathrm{O})}{N(\mathrm{H})} = \frac{N(\mathrm{O}^{+}) + N(\mathrm{O}^{+2})}{N(\mathrm{H})} \times \frac{N(\mathrm{He}^{+}) + N(\mathrm{He}^{+2})}{N(\mathrm{He}^{+})} .$$

Our results are plotted, for convenience, against electron temperature T_e (see Figure 2), although the apparent correlation with T_e is that which we would expect as a result of errors in the observed [O III] line intensities, and is probably not significant. Our results do, however, indicate that the oxygen abundance in planetary nebuale is lower by a factor of about 3 than the currently accepted cosmical value, $N(\mathrm{O})/N(\mathrm{H}) \sim 10^{-3}$.

Aller: This procedure differs from ours in that we have used the concentrations of trebly and quadruply ionized neon as derived from the [Ne IV] and [Ne V] lines to estimate the proportions of the more highly ionized oxygen atoms. Hence we derive a higher oxygen abundance. The problem should be re-examined with a more accurate ionization theory and models for the nebulae.