SOME ASPECTS OF CHEMICAL ABUNDANCE DETERMINATIONS IN PLANETARY NEBULAE

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The determination of the chemical compositions of gaseous nebulae in general and of planetary nebulae in particular is a difficult undertaking. The zeroth-order approximation is straightforward, the first approximation is challenging, and the second approximation is almost intractable.

The classical investigations of Bowen and Wyse (1939) and of Wyse (1942) entailed a quantum leap forward in the quality of observational data. The derivation of elemental abundances from line intensities was handled in an approximate, semi-quantitative manner. Nevertheless, they were able to conclude, quite correctly, that the chemical composition of planetary nebulae much more closely resembled that of the sun than one would infer from "a direct inspection of the observed intensities."

Bowen and Wyse were able to make the first serious attack on the problem because they were able to measure a great number of moderately weak and even some very weak lines in the spectra of gaseous nebulae. Considering the difficulties of using the photographic plate as a photometric tool, Wyse's calibrated eye estimates of intensity were remarkably good.

Fortunately, we can now measure spectral lines over a much greater range in wavelength and intensity and by much more accurate methods of data acquisition. Optical region data are now supplemented more and more by excellent infra-red and radio-frequency measurements. Fascinating new information is being supplied by spectrographs flown in satellites.

In 1945, in the 18th and final paper of Menzel's series entitled "Physical Processes in Gaseous Nebulae," an attempt was made to derive ionic concentrations in planetaries. This endeavor constituted a systematic effort to use an essentially modern formulation of recombination and forbidden line excitation rates. A hydrogenic theory was used to compute recapture and cascade rates and predict line intensities for

Yervant Terzian (ed.), Planetary Nebulae, Observations and Theory, 225-233.

CII, HeI, OII, etc. On the basis of these rather primitive calculations, it was argued, nevertheless, that there need be no discrepancy between the concentration of O++ ions estimated from the familiar [OIII] lines and that found from faint permitted OII lines that Wyse had observed in NGC 7009. Although the formulae necessary for the interpretation of forbidden line intensities in terms of ionic concentrations, densities, temperatures, etc. were given, the then available collision strengths were much too large. Menzel (1962), whose memory we honor in this symposium, has summarized much of the early work.

The theoretical picture is now greatly improved, thanks especially to the accurate methods developed by Seaton and his associates for calculation of collision strengths, improved transition probabilities by Garstang, by Czyzak and Krueger, by Nussbaumer, and by many others, and finally trustworthy continuous absorption coefficients plus direct and dielectronic recombination coefficients. Additional data are needed for a number of the less abundant elements up to calcium. Further charge exchange cross-sections are also required.

Here I would like to describe an abundance program in which much emphasis is placed on investigations of weak diagnostic lines and stratification effects in nebulae. This endeavor is being carried out in collaboration with S.J. Czyzak of Ohio State University. In certain aspects of the program we have also worked closely with J.B. Kaler. A basic tool for this investigation is the Robinson-Wampler image-tube scanner at the Cassegrain focus of the Lick Observatory 3-m telescope. The spectral resolution is sufficiently high for most purposes; with the red-sensitive cell we can cover the region from λ3700 to λ8600. Shortward of λ3700 it is necessary to use the green or blue image dissector at some sacrifice in resolution. Until now, in this region we have employed photo-electric measurements and photographic measurements for the weaker lines, the latter calibrated as far as possible by photoelectric photometry. I should like to emphasize that we have tried to calibrate the image tube scanner data photoelectrically using the excellent published values by Peimbert and Torres-Peimbert (1971, 77b), and the older measurements by O'Dell (1963), for example, supplemented also by observations with the Oke spectrum scanner which Czyzak and I have made with the 1.5, and 2.5m Mt. Wilson telescopes.

Then, with the calibrated image tube scanner data, we are able to reassess some of the earlier photographic measurements (λ4000 - λ5000) and also Lallemand tube data (Walker and Aller 1970). In the past it has been difficult to calibrate these electronic camera measurements photo-electrically since the weakest lines thus measurable were often too strong and few in number to establish zero points. Our basic calibration procedures are described in a recent paper on the spectrum of NGC 7027 (Kaler et al. 1976) and will not be discussed further here. Photographic measurements have been used only where no other data were available, e.g. for [NaIV], λ3242, 3362, or where high spectral resolution is required, e.g., separating weak λ3726, 3729 [OII] lines from overlapping Balmer transitions.

In making comparisons of data derived from different sources, it is important to recognize that the image-tube scanner (ITS) data refers to a small area; a slot 2" x 2" is normally used with the ITS. Modern photographic measurements usually entail narrow strips taken across nebular images (see e.g. Boeshaar 1974; Boeshaar et al. 1974). On the other hand, photoelectric scans often include the entire nebula. In objects such as NGC 6572 where the central region only was observed with the ITS, while photoelectric observations by the Peimberts and ourselves included the entire flux from the nebula, the influence of stratification effects is clearly shown.

Observations of nearly fifty planetaries have been secured with the image-tube scanner and data reduction has been completed for more than forty of them. For virtually all of these objects, we can derive [OIII] electron temperatures, [SII] and/or [OII] densities, and concentrations for various ions of helium, oxygen, nitrogen, neon, sulphur, chlorine, and argon. A survey, based on data available at the time of the Minkowski Symposium did not indicate a marked variation of chemical composition with distance from the galactic center (Aller 1976), as had been proposed by D'Odorico and Peimbert (1976) and by Peimbert and Torres-Peimbert (1977b). Composition differences appear connected with the central star's evolutionary state (Aller and Czyzak) and certainly with the parent stellar population type as shown for example by Miller (1969), Peimbert (1973), or by Boeshaar and Bond (1977). From observations of a large number of planetaries, Timothy Barker has suggested a relationship between orbital characteristics and chemical composition.

Here I would like to discuss some intensively observed high excitation planetary nebulae whose spectra show a number of diagnostic lines and emissions of [NaIV], [KIV], [KVI], [CaV], and iron in various ionization stages. The absence of certain necessary parameters notably collision strengths and continuous absorption coefficients for most of the observed ionization stages of iron excludes a satisfactory quantitative discussion for this element.

To obtain elemental abundances from ionic concentrations, we can proceed by empirical methods, by models, or by some combination of the two. As far as possible, we have endeavored to employ models, comparing predictions at each stage with observed ionic concentrations, and invoking empirical procedures when they seemed to be required.

Valuable contributions to calculations of models and their applications to nebulae have been made by Goodson (1967), Hummer and Seaton (1963), Flower (1969), Williams (1968), Harrington (1969), Kirkpatrick (1972), Buerger (1973), Webster (1976), Bohlin et al (1977), and others. Our own version based on one kindly supplied by Bruce Balick was developed by C.D. Keyes to include additional ions, influence of L α of HeII, dielectronic recombinations, and improved values of atomic parameters for collisions, A-values, absorption coefficients, etc. We chose central star temperatures ranging from 37,000°K to 150,000°K, employing black body curves for the very highest temperatures. We selected curved-atmosphere models calculated by Cassinelli (1971) for effective temperatures of 37,500K, 48,800K and 95,090K and non-LTE curved atmosphere models by Kunasz et al. (1975) for effective temperatures of 63,000K and 100,000K. Also we chose a variety of densities ranging from 10^3 to $10^4 cm^{-3}$, stellar radii ranging from slightly less than that of the sun for the cooler stars to a tenth of a solar radius or less for the very hottest objects. For the initial models we adopted nebular elemental abundances from recent compilations: the Peimberts (1977b), Czyzak and Aller (1973), Aller (1976) for the more abundant elements. For metals such as Na, K, and Ca we chose solar abundances (Ross and Aller 1976). In some very recently calculated models we have been influenced by results obtained by Bohlin et al. (1977) for NGC 7662.

We have concentrated on homogeneous models, mostly for reasons of simplicity and economy, but also because of the great range of additional arbitrary parameters otherwise required. In harmony with the results of previous workers in this field we have found that: (a) The predicted spectrum is strongly dependent upon the spectral energy distribution of the central star, and therefore upon its assumed chemical composition, non-LTE effects, and curvature of atmospheric layers. For stars whose visual region spectra show nothing unusual (either they are continuous or have weak absorption lines), we are optimistic about the use of carefully constructed model atmospheres such as those of Cassinelli or of Kunasz et al. (b) The radius of the central star does not appear to have great influence on the emergent nebular spectrum. (c) The density of the shell influences the results in a predictable way, changing the intensity ratio of density sensitive lines and the size of the Stromgren sphere. (d) In high excitation planetaries, L α of HeII can markedly influence the ionization structure. (e) The introduction of denser partial shells (to simulate inhomogenieties) and truncation of the nebula at various cut-offs before the Stromgren shell radius is reached have profound effects on the predicted line intensities. (f) Adjustments in abundances of primary coolants such as carbon can have a profound influence, as has been emphasized by Bohlin et al.(1977).

Calculation of some forty odd homogeneous model nebulae yielded theoretical spectra that looked like planetary nebulae spectra, but obstinately failed to reproduce the detailed spectral line intensities in our target objects. By going to non-homogeneous models, the fit could be improved, but at the price of increasing the number of adjustable parameters. With the high carbon abundances deduced by the Peimberts from the permitted carbon lines, the predicted electron temperature usually turns out to be lower than the one computed from the [OIII] lines. Modifying the energy distribution in the central star does not help much here, but lowering the carbon abundance does. Models often did not predict a 4686Å of HeII as strong as observed in objects such as NGC 2022, unless one assumed an inadmissably thin shell.

Satisfactory representations of the observed spectra of most of our high excitation nebulae cannot be achieved by homogeneous models. One has to introduce high density, low excitation blobs to represent all features from [SII] to [NeV]. An alternative procedure is to use the models as interpolation devices for ions over certain ranges of ionization potentials. Thus, if the models correctly reproduce the relative ionic concentrations of NeIII - NeV, ArIII - ArV, etc., we feel justified in using them to estimate the amount of sodium from [NaIV] lines or calcium from [CaV] lines. In high excitation nebulae, the abundances of elements such as nitrogen and sulphur that are represented only by low stages of ionization are more difficult to derive, since these emissions must arise only in low excitation, cool dense, blobs. Fortunately, oxygen which is observed [OI], [OII], and [OIII] helps to bridge the gap. Both empirical evidence (Hawley and Miller 1977) and lower excitation or full Stromgren sphere models (which simulate the lower excitation blobs) lend strong support to the approximation procedures suggested by Peimbert and Costero (1969). Here, the non-homogeneous models, including charge-exchange effects, would be useful but at this epoch an insufficient number of them have been generated.

Table 1 gives detailed results for five high excitation planetaries, including the old favorite, NGC 7662. NGC 7027 has not been included as there appears to be no hope of reproducing it by any straightforward model. NGC 3242 and NGC 6818 are fairly regular objects; the spectra of their central stars appear to be purely continuous. A central star appears to be visible in IC 2165 under conditions of good seeing. NGC 6886 has no visible central star; actually it may resemble in some respects objects such as NGC 6302, NGC 7027, or (86 - 8°1). For each element we give logN on the scale, logN(H) = 12.00.

TABLE I Results for Individual Nebulae
log N

	IC2165	NGC3242	NGC6818	NGC6886	NGC7662
He	11.04	10.94	11.00	11.02	11.03
C	9.23	9.39	9.27	9.38	9.36
N	7.90	7.70	8.04	8.03:	7.78
O	8.50	8.63	8.89	8.70	8.63
F		5.56?			5.38:
Ne	7.95	8.04	8.23	8.25	7.93
Na	5.40:	6.05	6.30	6.12	6.03
P				∿5.3:	
S	7.38	7.12	7.58:	7.30	7.25
Cl	5.10	5.13	5.02:	5.50	5.36
Ar	6.30	6.28	6.49	6.54	6.36
K	4.55		5.12	5.16	4.82
Ca	5.26		5.31	5.05	5.30

Table 2 compares the mean composition of these five objects with results obtained by other observers and with the solar composition. The second column gives the mean value of logN. The number in parentheses gives the "fluctuation", < Δ logN >, calculated as though it were a probable error for an abundance determination in a single nebula. The third column is included as an item of historical interest; these are the abundances derived in the last paper of Menzel's series entitled "Physical Processes in Gaseous Nebulae." The abundances of helium and carbon were found essentially from a hydrogenic recombination theory; those of other elements on the basis of collision strengths that were much too large. Column (4) gives the mean nebular composition as presented at the Menzel symposium (Aller 1971) and at the Liege 1972 planetary nebula symposium (Czyzak and Aller 1973). At that time, somewhat less data were available for spectral regions longward of 5900Å. Results for elements given in ( ) were mostly estimated from older measurements in NGC 7027. The Peimbert data given in the next column have been derived from a large number of nebulae. The sixth column gives results obtained by Bohlin et al. (1977) from a careful model analysis involving observations of NGC 7662 secured from above the earth's atmosphere. They found important diagnostic lines of C, He, and Ne. The seventh column lists solar abundances as compiled by Ross and Aller (1976). These authors give estimated errors for individual elements, which are useful in making comparisons.

TABLE II Comparison of Nebular Results

log N

	Present Study 1977		1945	1973	Peimberts 1977	BSH NGC7662 1977	Solar
He	11.01		11.00	11.09	11.04	10.96	10.8±0.2
C	9.33	(0.05)	8.8:	8.7:<	9.5	8.57	8.62±0.12
N	8.00	(0.15)	8.30	8.12±12	8.33	7.90	7.94±0.15
O	8.69	(0.09)	8.40	8.85±.15	8.87	8.57	8.84±0.07
F	5.4:		(5.)	(4.9)			4.56±0.33
Ne	8.10	(0.09)	7	8.2±0.1	8.28	7.85	7.57±0.12
Na	6.06	(0.14)		(6.6)			6.28±0.05
P	5.3						5.50±0.15
S	7.35	(0.11)	7.6	(7.9)		6.90	7.2 ±0.15
Cl	5.26	(0.12)	6.3	(6.9)			5.5 ±0.4
Ar	6.40	(0.07)	6.2	(7.0)			6.0 ±0.2
K	4.98	(0.14)		(5.7)			5.16±0.1
Ca	5.24	(0.27)		(6.4)			6.35±0.10

In comparing these numbers, we must realize that the nebular means quoted refer to somewhat different samples. The Peimberts included a large number of objects while the analysis presented here refers to only five high-excitation nebulae. Further differences may arise from the fact that we have observed only small selected regions in individual nebulae and have not used the same atomic parameters.

The results for helium appear to be in good accord, especially among the most recent measurements. We have not included objects such as NGC 6302 that appear to have excess amounts of helium. The solar abundance of helium is very poorly determined.

Carbon presents an engaging problem. The old 1945 efforts, the 1971 Menzel symposium estimate, the Peimberts' results, and the data presented in Table I all involve the use of permitted lines, especially 4267Å - although we have also used the CIV 5812Å transition as a guide on the ionization structure. In the Orion nebula, the recent comprehensive analysis by the Peimberts (1977a) gives logN (C) = 8.55 which falls not far from the solar value 8.62, and supersedes an earlier determination (Aller 1972) for Orion which gave 8.37. Substantial evidence (Kaler 1972), Grandi 1972) indicates that observed nebular permitted line intensities exhibit a mixture of recombination and stellar or nebular resonance fluorescence effects. Objects may differ remarkably from one another in this respect. For example, NGC 6778 shows unusually prominent permitted lines. Bohlin et al. (1977) measured the strong ultraviolet CIII and CIV lines to obtain an essentially solar carbon abundance.

Nitrogen shows pronounced abundance fluctuations. The average of our small sample shows no nitrogen excess as compared with the sun, whereas the Peimberts do find a nitrogen excess. Their average nitrogen abundance is similar to the value we found for NGC 6886.

Oxygen has a mean abundance similar to the solar value according to the Peimberts and our earlier compilation. In the present sample, oxygen may have a lower than solar abundance.

Both neon and argon appear to be more abundant in the nebulae than in the sun. Our Ne/O ratio is smaller than that found by Kaler (1973); the Ar/O ratio is substantially lower.

The data for fluorine and phosphorus are very poor. The solar fluorine abundance is badly determined so that the ten-fold discordance between solar and nebular results may be spurious. The phosphorus abundance, derived from a single weak line, 7876Å, in a single nebula is probably essentially solar.

Sulphur and chlorine are observed in many nebulae, including objects of low excitation. In the high excitation objects here considered, they appear to have essentially solar abundances. The solar chlorine abundance is badly determined.

Although the sodium and potassium abundances appear to fall about 2 dex below the solar values, I do not regard this difference as significant in view of the fact that few ionization stages are observed for these elements, all the observed lines are weak, and we depend strongly on models.

On the other hand, there seems little doubt that calcium is strongly depleted in the objects studied here. This element forms refractory compounds and may be taken up in grains, as Shields (1975) suggested for a depletion of iron in NGC 7027.

These efforts constitute only a reconnaissance. As the ultraviolet and infra-red spectral regions of planetary nebulae are intensively explored, many present uncertainties can be eliminated. The carbon abundance problem is most striking, but [NeIV] nebular line data combined with auroral line data can give much needed information on electron temperatures in interiors of high excitation nebulae. Permitted lines of well-ionized oxygen and nitrogen will enable us to fill in the gaps for missing ionization stages and thereby alleviate one of the most vexing troubles of nebular abundance determinations.

This program was supported in part by National Science Foundation grant #AST - 21457 to University of California, Los Angeles. The services of the UCLA campus computing network are gratefully acknowledged. Particular thanks are due to Mr. C.D. Keyes who played an indispensable role in the program from acquiring the observations to calculating the nebular models, and to Bruce Balick who supplied the initial program for model calculations. Mr. Theodore Stecher kindly sent me a preprint of his, Bohlin's, and Harrington's exciting paper on NGC 7662.

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DISCUSSION

Nussbaumer: The solar photosphere's abundance appears to be $O/H \approx 6x10^{-4}$. The coronal abundance determinations give much lower values, $O/H = 2x10^{-4}$. We also obtained O/Ne = 8. This discrepancy should not be overlooked when quoting solar abundances.

Aller: I vigorously disagree that the solar oxygen abundance derived from photospheric lines is in error by a large factor. I quite agree that abundances derived from the behavior of oxygen lines in the chromosphere-corona transition zone under conditions of extreme non-LTE effects can differ from photospheric values, and that there are uncertainties in the coronal value. A large body of Fraunhofer line data, however, give a consistent picture.