On nitrogen abundances of planetary nebulae

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On nitrogen abundances of planetary nebulae

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Summary. Observations of N II recombination lines in the planetary nebula NGC 3242 are presented which allow the first temperature independent measurement of the nitrogen abundance of a nebula. Model nebula calculations are utilized to identify a reliable N/H indicator. The standard technique employing strong forbidden lines and the approximation that $N/O \simeq N^+/O^+$ may introduce systematic errors greater than 25 per cent. A good compromise is to set $N/He = (N^{2+} + N^+)/He^+$. The N/H abundance deduced in this manner is in reasonable ($\simeq$ 25 per cent) agreement with that deduced from the standard analysis.

1 Introduction

Determinations of the nitrogen abundances of planetary nebulae serve as important probes of galactic and stellar evolution (see, e.g. Kaler, Iben & Becker 1978). Reliable measurements present severe observational problems, however, since no strong optical lines from dominant stages of ionization are seen (the [N II] λλ 6548, 6584 doublet is strong in some nebulae, but N^+ is expected to be only a trace ionization stage). Indirect methods of measurement of N/H must therefore be utilized.

The most common method of determining N/H is to assume that

$$\frac{N^+}{O^+} = \frac{N}{O} \tag{1}$$

and then to scale this abundance ratio by the more easily measured oxygen abundance. The great popularity of this approach is largely attributable to the great strengths of the [N II] and [O II] lines in gaseous nebulae, since there is only weak theoretical justification for

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equation (1). Models have long encountered difficulty in reproducing the absolute intensities of [N II] and [O II] lines, although this problem has eased considerably following the recognition of the importance of charge exchange reactions (Péquignot, Aldrovandi & Stasinska 1978). The general validity of equation (1) is open to question, since both N^+ and O^+ are strongly affected by charge exchange (Field & Steigman 1971; Butler, Bender & Dalgarno 1979).

In the next section, model nebula calculations are presented which incorporate the most recent estimates of the rates of charge exchange reactions, and the question of what might constitute a reliable N/H indicator is addressed. These models reveal that equation (1) can be in error by as much as 50 per cent and suggest that a better approach for planetary nebulae would be to set

$$\frac{N}{He} = \frac{(N^+ + N^{2+})}{He^+}$$

and then to scale through the more readily measured helium abundance. Observations of N II recombination lines in the planetary nebula NGC 3242 are presented in Section 3. These measurements allow the first temperature independent determination of the nitrogen abundance of a planetary nebula. A discussion of the significance of these results follows.

2 Nitrogen in planetary nebulae

Model calculations are presented in this section in an attempt to identify an appropriate N/H indicator. Fig. 1 shows the ionization structure of a typical planetary nebula. The model was computed with the program described by Ferland & Truran (1981), which is

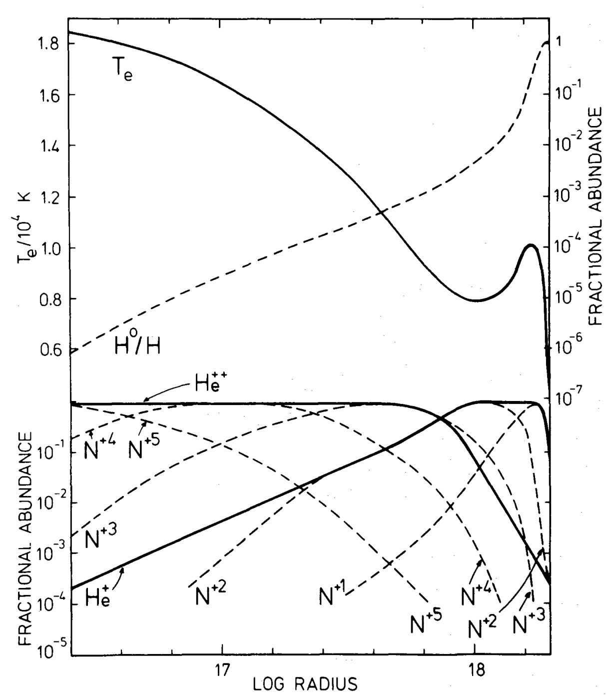

Figure 1. Model calculations. This figure shows the thermal and ionization structure of a typical planetary nebula. The nebula has a density of $10^3\,cm^{-3}$, a filling factor of 0.1, and is ionized by a 10^5 K blackbody with total luminosity $L = 10^{37.6}\,erg\,s^{-1}$. The upper panel shows the temperature and neutral hydrogen fraction as a function of radius, while the lower half shows the fractional abundance of several stages of ionization of helium and hydrogen. Nitrogen is either singly or doubly ionized in the He^+ zone.

Table 1. Calculated emission line intensities.

Ion	λ	I/I (Hβ)
H I	4861	1.00
He I	10830	0.47
He I	5876	0.14
He II	4686	0.11
[N II]	6584	2.41
[O I]	6300	0.43
[O II]	3727	5.63
[O III]	5007	10.6
[Ne III]	3869	0.58
[Ar III]	7135	0.37

Model parameters:

$L_* = 10^{37.6}\,\mathrm{erg\,s^{-1}}$ $N_{\mathrm{H}} = 10^3\,\mathrm{cm^{-3}}$

$T_* = 10^5\,\mathrm{K}$ $\epsilon = 10^{-1}$

very similar to those described by Williams (1967), Davidson (1972), MacAlpine (1972), Shields (1978), Netzer (1976), and Péquignot *et al.* (1978). All known charge exchange reactions have been fully incorporated in these calculations (see Dalgarno 1978; Butler *et al.* 1979; Butler, Heil & Dalgarno 1980; Butler & Dalgarno 1980). Since both the computational techniques and the atomic data base employed by the program are quite similar to those described in the papers mentioned above, details will not be rediscussed here.

2.1 MODEL PARAMETERS

The model illustrated in Fig. 1 is not meant to reproduce any particular nebula, but is typical of high ionization objects. The central star is a blackbody radiator with a temperature of 10^5 K and a luminosity of $10^{37.6}\,\mathrm{erg\,s^{-1}}$. The surrounding nebula has a solar chemical composition (11 elements, H, He, C, N, O, Ne, Mg, Si, S, Ar, Fe, are included with solar abundances taken from Lambert (1978), Lambert & Luck (1978) and Cameron (1973)) and consists of a set of filaments with density $N_{\mathrm{H}} = 10^3\,\mathrm{cm^{-3}}$ and filling factor $\epsilon = 0.1$. These parameters are typical of systems mid-way along the Harman–Seaton (1966) sequence. Model parameters and the intensities of some of the stronger optical emission lines (actually over 100 collisionally excited lines are included in the cooling rate) are summarized in Table 1. These predictions are in general agreement with typical observed values. Two additional models, with $T_* = 7.5 \times 10^4$ and 1.25×10^5 K but other parameters held fixed, have also been computed as a check on the sensitivity of our results to details of the models.

2.2 IONIZATION FRACTIONS

The validity of equation (1) and other possible means of measuring N/H are discussed in this section. Table 2 summarizes some ionic abundance ratios predicted by the models. The first column of the table gives the ratio $\langle N^+/N \rangle / \langle O^+/O \rangle$, averaged over volume. The ionic ratio exceeds the abundance ratio for all three models because the $O^+ + H^0 \rightarrow H^+ + O^0$ reaction is much faster than the corresponding reaction involving N^+ (Field & Steigman 1971; Butler & Dalgarno 1979).

The third column of the table gives the apparent N/O ratio, as deduced through the standard analysis, relative to the true abundance ratio. The apparent ratio was obtained by

Table 2. Ionic abundance ratios.

T_*	$\langle N^+/N\rangle/\langle O^+/O\rangle$	$\frac{N/O^{\star}\text{ apparent}}{N/O\text{ true}}$	$(\langle N^+/N\rangle + \langle N^{2+}/N\rangle)/\langle He^+/He\rangle$
7.5×10^4	1.39	0.78	0.85
10.0×10^4	1.53	0.95	0.86
12.5×10^4	1.61	1.10	0.87

★ N/O ratio deduced from [N II] and [O II] lines, as described in the text.

performing a standard analysis on the predicted emission line spectra: the electron temperature was measured from the [O III] 5007/4363 ratio, and this temperature and equation (1) were used to convert the [N II] λ6584/[O II] λ3727 intensity ratio into an abundance ratio. Fortuitously, the large change in T_e between the O^{2+} and O^+ zones illustrated in Fig. 1 largely compensates for errors in equation (1). The size and direction of the error is sensitive to details of the models, and could be larger for other values of the parameters. (This study was motivated by earlier calculations, performed before the publication of the most recent charge exchange rates, which indicated apparent abundances in error by factors of 2–3.)

Simple ionization potential arguments and the model calculations shown in Fig. 1 suggest that the nitrogen abundance could be measured more reliably by assuming that

$$\frac{N}{He}=\frac{(N^+ + N^{2+})}{He^+}. \tag{2}$$

The last column of Table 2 lists the ratio $(\langle N^+/N\rangle + \langle N^{2+}/N\rangle)/\langle He^+/He\rangle$, again averaged over volume. Equation (2) is valid to ~ 15 per cent, and, unlike equation (1), is fairly insensitive to details of the model.

Although measurement of the N^+/He^+ ionic abundance ratio is straightforward using the strong [N II] λλ6548, 6584 and He I λ5876 lines, doubly ionized nitrogen produces no strong optical lines and measurement of its abundance is more difficult. The N II λ5680 RMT 3 recombination lines, a set of six transitions isoelectronic with the O III λλ3341, 3312, 3299 multiplet studied by Burgess & Seaton (1960), provides a reliable indicator of the N^{2+} abundance. The effective recombination coefficient for this multiplet has been estimated by scaling Burgess and Seaton's results for O III through the relationship

$$\alpha[z, T_e]=\frac{z}{z'}\alpha[z', T_e\,(z/z')^{-2}]\ ,$$

where z is the ionic charge before recombination. This scaling suggests that the effective recombination coefficient for all lines of the multiplet is

$$\alpha^{\text{eff}}(5680) = 5.2\times10^{-13}\,T_4^{-0.84}\ \text{cm}^3\,\text{s}^{-1}.$$

3 Observations

Moderate resolution (δλ ~ 1 Å) spectrophotometric observations of the bright southern planetary nebula NGC 3242 over the wavelength interval λλ5300–6300 Å have been carried out with the Image Photon Counting System mounted on the RGO Spectrograph at the *f*/8 Cassegrain focus of the 4-m reflector at the Anglo-Australian Observatory. The

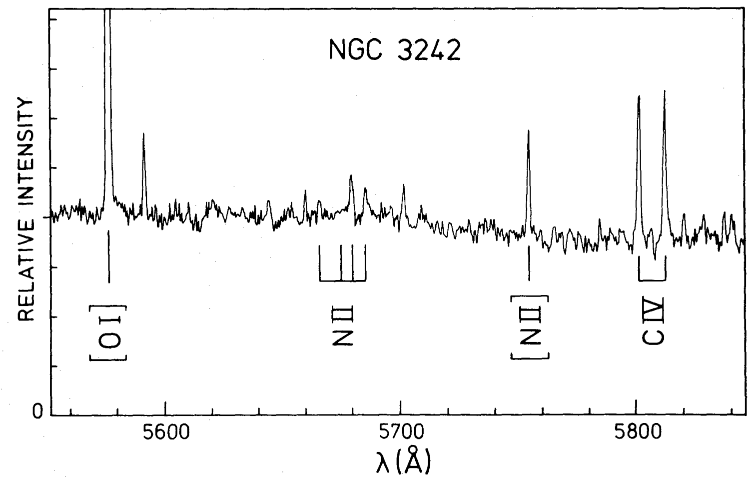

Figure 2. Spectrophotometric observations. This figure shows a small portion of a moderate resolution ($\delta\lambda = 1$ Å) observation of NGC 3242. Some of the stronger lines are identified. Positions of components of the N II recombination multiplet are marked. The relative intensities of individual components are in reasonable agreement with expectations.

Table 3. N II line intensities.

λ	*i–j*	*I*/*I*(5876)
5666.9	1–2	6.4 (–4)
5676.1	0–1	4.7 (–4)
5680.1	2–3	16.8 (–4)
5686.2	1–1	17.9 (–4)
5730.7	2–1	3.7 (–4)

spectrometer was used with a long slit ($s = 1$ arcmin) to observe a cut across the bright inner nebula just south-west of the central star. A portion of the scan is shown in Fig. 2, where the positions of components of the N II multiplet and some of the stronger emission lines are marked.

Table 3 summarizes the intensities of the N II lines relative to He I 5876. The integrated strength of the multiplet, $I(5680)/I(5876) = 5.0 \pm 0.5 \times 10^{-3}$, corresponds to $N^{2+}/He^+ = 4.6 \times 10^{-4}$.

The bright inner nebula has been well studied (see, e.g. Barker 1978; Kaler 1980a, b). Kaler finds He/H = 0.11, $N^+/O^+ = 0.15$, O/H = 4.2×10^{-4}, $O^+/O = 10^{-2.3}$, and N/H = 6.3×10^{-5}. Since only a few per cent of the nitrogen is singly ionized, we find N/H = $[N^{2+}/He^+]$ [He/H] = $5.1 \pm 0.5 \times 10^{-5}$, in good agreement with the standard analysis.

4 Discussion

We have shown that the nitrogen abundance deduced through a popular indirect analysis employing strong forbidden lines is within 25 per cent of the value obtained through a direct measurement employing recombination lines. The difference between the two methods of measuring N/H is close to that predicted by the model calculations. This is an important confirmation that our general understanding of the physical processes governing formation of N^+ and O^+ is now complete. It remains possible that, for nebulae characterized by different physical conditions, more pronounced discrepancies might result. We emphasize that the assumption N/He = $(N^+ + N^{2+})/He^+$ should generally yield a more reliable measure of the nitrogen abundance.

Acknowledgments

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