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The O III 52 μm/88 μm Emission-Line Ratio in Planetary Nebulae

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Abstract. *R*-matrix calculations of electron impact excitation rates in O III are used to derive the electron-density-sensitive emission-line ratio $R = I\,(2s^2\,2p^{2\;3}P_2 - 2s^{\,2}2p^{2\;3}P_1)/I\,(2s^22p^{2\;3}P_1 - 2s^22p^{2\;3}P_0) = I\,(52\mu\text{m})/I\,(88\mu\text{m})$ for a range of electron temperatures (T_e = 5000–20000 K) and densities (N_e= 10–10^5 cm^{-3}) applicable to planetary nebulae. Electron densities deduced from the observed values of *R* in several planetary nebulae are in excellent agreement with those deduced from C1 III and Ar IV, which provides support for the accuracy of the atomic data adopted in the calculations.

Key words: emission-line diagnostics—electron densities—planetary nebulae

1. Introduction

Emission lines arising from transitions in ions of the carbon isoelectronic sequence have been frequently observed in the spectra of astronomical and laboratory plasmas (Keenan, Aggarwal & Berrington 1988; Keenan *et al.* 1988a; Davé *et al.* 1987; Stratton *et al.* 1987). Of particular interest are lines from O III, which have been detected in a wide variety of astronomical objects, including planetary nebulae (Aller & Keyes 1987), Seyfert galaxies (De Robertis 1987), QSOs (Filippenko 1985), H II regions (Evans & Dopita 1985), late-type stars (Basri, Linsky & Eriksson 1981) and the Sun (Widing, Feldman & Bhatia 1986). These transitions may be used to infer the electron temperature and density of the emitting region through diagnostic line ratios, although to calculate these reliably accurate atomic data must be employed, especially for electron impact excitation rates and oscillator strengths (Dufton & Kingston 1981), Several diagnostics have been developed over the past few years involving optical and ultraviolet lines in O III, probably the most accurate being those of Aggarwal (1985), Keenan & Aggarwal (1987) and Keenan *et al.* (1988b), which employ the electron impact excitation rates of Aggarwal (1983, 1985) calculated with the *R*-matrix code (Burke & Robb 1975; Berrington *et al.* 1978).

Emission lines of O III have also been observed in the far-infrared region of the spectra of gaseous nebulae (Lester *et al.* 1987; Rubin *et al.* 1988; Watson *et al.* 1981) at wavelengths of 52 μm ($2s^22p^{2\;3}P_2 - 2s^22p^{2\;3}P_1$) and 88 μm ($2s^22p^{2\;3}P_1 - 2s^22p^{2\;3}P_0$). In this paper we use the Aggarwal (1983, 1985) electron excitation rate calculations to derive the emission line ratio $R = I(52\mu m)/I(88\mu m)$, and show that it is a useful density diagnostic for planetary nebulae.

2. Atomic data

The model ion adopted for O III was similar to those for other carbon-like ions such as Ca XV and Ne V discussed by Keenan and his co-workers (see, for example, Keenan, Aggarwal & Berrington 1988; Keenan *et al.* 1986, 1988a). Briefly, the 9 energetically lowest LS states were included in the calculation *viz.* $2s^22p^2\ ^3P$, ^1D, ^1S; $2s2p^3\ ^5S$, ^3D, ^3P, ^1D, ^3S and ^1P, making a total of 15 levels when the fine-structure splitting in the triplet terms was taken into account. Energies of all the ionic levels were taken from Moore (1971).

Electron impact excitation rates in O III were obtained from Aggarwal (1983,1985), while for Einstein *A*-coefficients the results of Froese Fischer & Saha (1985) were adopted. As noted by, for example, Seaton (1964), proton excitation may be important for transitions with small excitation energies, *i.e.* fine-structure transitions such as that in the $2s^22p^5\ ^2P$ ground term of Fe XVIII (Keenan & Reid 1987). However at the temperatures we are interested in excitation by protons is negligible and hence was not included in the calculations. For example, at T_e = 20000 K, protons add only 1–2 percent to the total excitation rates of the $^3P_0–^3P_1$, $^3P_0–^3P_2$ and $^3P_1–^3P_2$ transitions in the $2s^22p^2\ ^3P$ ground term of O III (Aggarwal, Baluja & Tully 1982).

3. Results and discussion

Using the atomic data discussed in Section 2 in conjunction with the statistical equilibrium code of Dufton (1977), relative O III line strengths were deduced for a range of electron temperatures (T_e= 5000–20000 K) and densities (N_e = 10–10^5 cm $^{-3}$) applicable to planetary nebulae (Kaler 1586; Barlow 1987). The following assumptions were made in the calculations: (i) that ionization to and recombination from other ionic levels is slow compared with bound-bound rates, (ii) that photoexcitation and de-excitation are negligible in comparison with the corresponding collisional rates, (iii) that all transitions are optically thin. Further details of the procedures involved may be found in Dufton (1977) and Dufton *et al.* (1978).

In Fig. 1 we plot the emission line ratio $R = I(52\ \mu m)/I(88\ \mu m)$ as a function of electron density at three electron temperatures, namely T_e = 5000,10000 and 20000 K; the results are also given in Table 1. It may be seen that the density sensitivity of the ratio is quite large, with R varying by a factor of approximately 16 between N_e = 10 and 10^5 cm^{-3}. However the temperature sensitivity is small with, for example, a factor of 2 change in T_e resulting in a 12 per cent or less variation in R. We note that our line ratios differ by up to 20 per cent from those calculated by Dinerstein, Lester & Werner (1985). These discrepancies are principally due to the adoption of improved electron impact excitation rates in the present analysis (see Aggarwal 1985 and Keenan & Aggarwal 1987 for more details).

The R ratios in several planetary nebulae have been obtained by Dinerstein, Lester & Werner (1985) using the 91-cm telescope of NASA's Kuiper Airborne Observatory

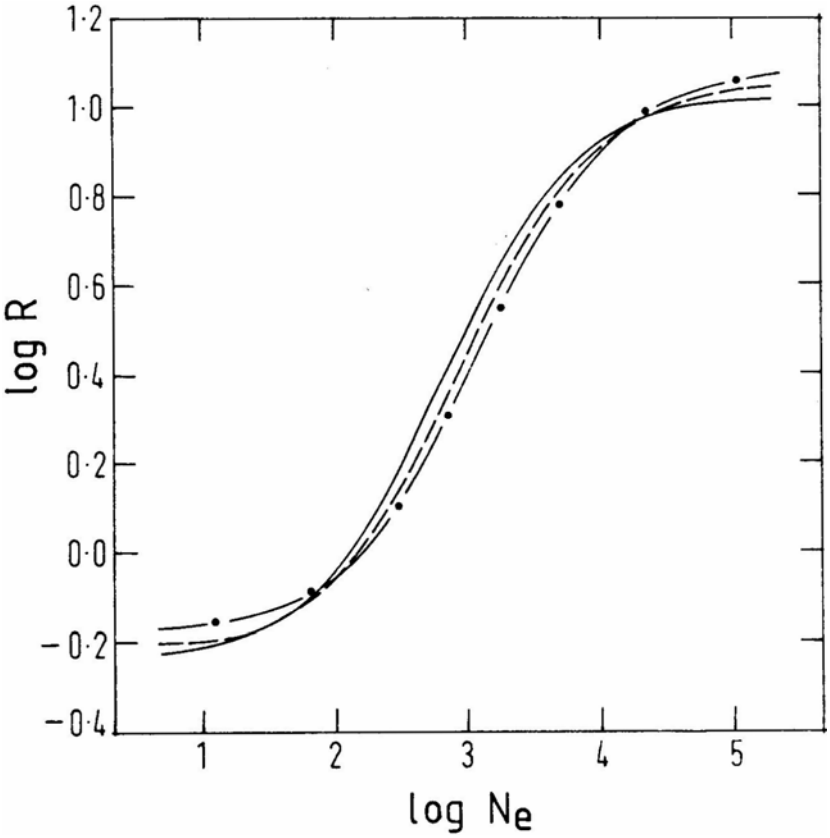

Figure 1. The theoretical O III emission line ratio $R = I(2s^2 2p^{2\,3}P_2 - 2s^2 2p^{2\,3}P_1) / I(2s^2 2p^{2\,3}P_1 - 2s^2 2p^{2\,3}P_0) = I(52\ \mu m)/I(88\ \mu m)$, where I is in energy units, plotted as a function of electron density at electron temperatures of 5000 K (*solid line*), 10000 K (*dashed line*) and 20000 K (*dash-dot line*).

Table 1. The theoretical OIII emission line ratio $R = I(52\ \mu m)/I(88\ \mu m)$, where I is in energy units.

	T_e(K)		
$\log N_e$	5000	10000	20000
1.0	6.10−1	6.30−1	6.84−1
1.5	6.84−1	6.88−1	7.32−1
2.0	9.13−1	8.69−1	8.80−1
2.5	1.57+0	1.40+0	1.32+0
3.0	3.16+0	2.77+0	2.51+0
3.5	5.82+0	5.32+0	4.94+0
4.0	8.34+0	8.13+0	7.99+0
4.5	9.74+0	9.88+0	1.01+1
5.0	1.03+1	1.06+1	1.10+1

$A \pm B$ implies $A \times 10^{\pm B}$

Table 2. Observed values of the emission line ratio R = I(52 μm)/I(88 μm) in planetary nebulae (taken from Dinerstein, Lester & Werner 1985) and the derived electron densities.

Planetary nebula	T_e K	log R	log$N_e(R)$	logN_e(Cl III, Ar IV)
NGC 2440	13500[a]	0.55	3.2	3.5[c]
NGC 3242	11300[b]	0.43	3.0	3.2[d]
NGC 6543	8100[b]	0.90	3.9	3.9[e]
NGC 6826	11200[b]	0.58	3.2	3.4[f]

[a] from Keenan & Aggarwal (1987)
[b] from Kaler (1986)
[c] observational data from Shields *et al.,* (1981)
[d] observational data from Barker (1978)
[e] observational data from Saraph & Seaton(1970)
[f] observational data from Aller & Czyzak (1983)

(KAO) in conjunction with a Fabry-Perot spectrometer. These observations are summarized in Table 2, along with the electron temperatures of the O III emitting regions in the nebulae, and the electron densities derived from R. Also listed in the table are the average values of log N_e estimated from line ratios in ions that have similar ionization potentials and spatial distributions to OIII, namely Cl III I(5518Å)/I(5538Å) and Ar IV I(4711Å)/I(4740Å). The sources of the Cl III and Ar IV observational data are given in the footnotes to the table. However the line ratio calculations used for these ions are those discussed by De Robertis, Dufour & Hunt (1987), as these employ the most accurate atomic physics data currently available.

We should point out that Keenan & Aggarwal (1987) found log N_e = 4.1 for NGC 2440 from the O III line ratio $R_2 = I(2s2p^3\ ^5S - 2s^22p^2\ ^3P_{1,2})/I(2s^22p^2\ ^1D - 2s^22p^2\ ^3P_{1,2})$ = I(1661Å + 1667Å)/I(4960Å + 5009Å), which is approximately a factor of 8 larger than log $N_e(R)$ in Table 2. However as the observed value of R_2 in NGC 2440 (R_2 = 0.023, Shields *et al.* 1981) is close to the theoretical low density limit (R_2 = 0.020 for $N_e \leqslant 10^4 \text{cm}^{-3}$, Keenan & Aggarwal 1987), the value of log N_e estimated from R_2 is probably unreliable.

An inspection of Table 2 reveals that the densities deduced from R and from CI III and Ar IV are in excellent agreement, with discrepancies of typically less than 0.2 dex. This provides observational support for the accuracy of the atomic data adopted in the present analysis, and also for the methods employed to derive the theoretical line strengths.

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