[O III] Electron Temperatures in Planetary Nebulae

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Received 1988 October 3; accepted 1989 February 8

Abstract. Relative level populations for O III, derived using electron impact excitation rates calculated with the R-matrix code, are used to deduce the electron-temperature-sensitive emission-line ratio

\[ R = \frac{I(2s^22p^2 \, ^1D - 2s^22p^2 \, ^1S)}{I(2s^22p^2 \, ^3P_{1,2} - 2s^22p^2 \, ^1D)} = \frac{I(4363 \, \text{Å})}{I(4959 + 5007 \, \text{Å})} \]

for a range of \( T_e = (7500-20000 \, \text{K}) \) applicable to planetary nebulae. Electron temperatures deduced from the observed values of \( R \) in several planetary nebulae are in excellent agreement with those determined from \( T_e \)-sensitive line ratios in other species, including C III]/C II, [N II] and [Ar III], which provides support for the accuracy of the atomic data adopted in the level population calculations.

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

1. Introduction

Emission lines arising from transitions among the \( 2s^22p^2 \, ^3P, ^1D \) and \(^1S\) levels of O III are frequently observed in the visible (Aller & Keyes 1987), infrared (Dinerstein, Lester & Werner 1985) and ultraviolet (Clegg et al. 1987) spectra of planetary nebulae. However, all these lines probably the most important are \( ^3P_{1,2} - ^1D \) at 4959 Å and 5007 Å, and \(^1D - ^1S\) at 4363 Å, as they allow the electron temperature to be inferred from the \( I(4363 \, \text{Å})/I(4959 + 5007 \, \text{Å}) \) intensity ratio (see, for example, Czyzak, Keyes & Aller 1986). Under normal planetary nebulae conditions, where \( N_e < 10^5 \, \text{cm}^{-3} \) (Barlow 1987), the 4363, 4959 and 5007 Å transitions are in the ‘coronal approximation’ (Elwert 1952), so that their intensities depend almost exclusively on the magnitude of the electron impact excitation rates for the lines. Hence to calculate the \( I(4363 \, \text{Å})/I(4959 + 5007 \, \text{Å}) \) ratio reliably, it is important that accurate data are employed for this atomic process.

Currently, the most accurate electron excitation rates available for O III are probably those of Aggarwal (1983, 1985), which have been calculated with the R-matrix code (Burke & Robb 1975; Berrington et al. 1978). In this paper we employ these atomic data to derive the \( I(4363 \, \text{Å})/I(4959 + 5007 \, \text{Å}) \) ratio and use it as a \( T_e \) diagnostic for several planetary nebulae whose electron temperatures have been independently determined from line ratios in other species. This should allow the validity of the Aggarwal excitation rates to be properly tested.
2. Theoretical ratios

Level populations for a wide range of electron densities and temperatures have been published for O III by Keenan & Aggarwal (1987), who employed the electron impact excitation rates of Aggarwal (1983, 1985) in their calculations. Briefly, the lowest nine LS states \((2s^22p^2 \, ^3P, \, ^1D; \, 1S; \, 2s2p^3 \, ^5S, \, ^3D, \, ^3P, \, ^1D, \, ^3S\) and \(^1P\)) were included in the model ion, leading to fifteen levels when the splitting in the triplet states was taken into account. Only collisional excitation and de-excitation by electrons and spontaneous radiative de-excitation processes were considered, and the plasma was assumed to be optically thin. Further details may be found in Keenan & Aggarwal (1987).

As noted by, for example, Keenan, Widing & McCann (1989), level populations may be used to derive emission line ratios \(R\) through the expression:

\[
R = \frac{I(\lambda_{ij})}{I(\lambda_{mn})} = \frac{N_j}{N_n} \cdot \frac{A_{ji}}{A_{nm}} \cdot \frac{\lambda_{mn}}{\lambda_{ij}}
\]  

(1)

where \(\lambda_{ij}\), \(\lambda_{mn}\) and \(I(\lambda_{ij})\), \(I(\lambda_{mn})\) are the wavelengths and intensities (in energy units) of the lines, respectively, \(N_j\) and \(N_n\) are the upper level populations of the relevant transitions and \(A_{ji}\) and \(A_{nm}\) are the Einstein \(A\)-coefficients. In Fig. 1 we use the Keenan & Aggarwal (1987) data to plot the emission line ratio \(R = I(4\,D - \, ^1S)/I(3\, P_{1,2} - \, ^1D) = I(4363 \, \text{Å})/I(4959 + 5007 \, \text{Å})\) as a function of electron temperature at a density of \(N_e = 10^3 \, \text{cm}^{-3}\), although we note that it is density insensitive for \(N_e < 10^5 \, \text{cm}^{-3}\).

Our calculations of \(R\) will lead to electron temperature estimates approximately 200 K higher than those that would be derived using the atomic data summarised by Mendoza (1984) for the five energetically lowest levels in O III. This discrepancy is partly due to the fact that in the present paper theoretical line strengths have been derived with a fifteen level model ion, as opposed to the five level one necessary when

![Figure 1. The theoretical [O III] emission line ratio \(R = I(2s^22p^2 \, ^1D - 2s^22p^2 \, ^1S)/I(2s^22p^2 \, ^3P_{1,2} - 2s^22p^2 \, ^1D) = I(4363 \, \text{Å})/I(4959 + 5007 \, \text{Å}),\) where \(I\) is in energy units, plotted as a function of electron temperature at an electron density of \(N_e = 10^3 \, \text{cm}^{-3}\).](image-url)
using the Mendoza compilation. In addition, the electron impact excitation rate calculations of Aggarwal (1983, 1985) are an improvement over the results of Baluja, Burke & Kingston (1980, 1981) referenced by Mendoza, as discussed in detail by Keenan & Aggarwal (1987).

3. Results and discussion

Many authors have determined the $R$ ratios in planetary nebulae (see, for example, Aller & Keyes 1987), although there are relatively few for which electron temperatures have been independently estimated from a number of $T_e$-sensitive ratios in other species. In Table 1 we summarise $R$ ratios for several planeristars, along with the sources of the observational data. Also listed in the table are the electron temperatures ($T_e(R)$) derived from $R$ and the mean values ($\tilde{T}_e$) deduced from line ratios in ions that have similar spatial distributions to O III, namely $I$(C iii) 1909 Å)/$I$(C ii 4267 Å) discussed by Kaler (1986a), $I$(5755 Å)/$I$(6548 + 6583 Å) in [N ii] (Kaler 1986b) and $I$(7136 + 7751 Å)/$I$(5192 Å) in [Ar iii] (Keenan, Johnson & Kingston 1988). These references also contain the sources of the observational data used in the electron temperature determinations.

An inspection of Table 1 shows that the [O III] electron temperatures are in excellent agreement with the mean values determined from several independent $T_e$ diagnostics. Discrepancies in the two sets of results are typically 1400 K, and only exceed 2000 K in one case, namely that of NGC 6302. Even in this instance we note that an increase in the observed $R$ ratio for NGC 6302 of only 0.1 dex will completely remove the disagreement between $T_e(R)$ and $\tilde{T}_e$. These results provide observational support for both the accuracy of the atomic data adopted in the [O III] line ratio calculations, and the techniques used to derive the theoretical values of $R$.

Acknowledgements

We would like to thank Professors P. G. Burke FRS and H. B. Gilbody for their continued interest in this work. FPK is grateful to the United Kingdom Science and Engineering Research Council for financial support.
References