Recombination Line Spectroscopy : The OII Spectrum in Low Density Nebulae

Rob Bastin and Peter Storey, University College London

Introduction

In astrophysical ionised plasmas, weak recombination lines are increasingly being used to determine physical properties. Recent observations have allowed us to observe transitions of doubly ionised species (e.g. 4f-3d of OII) for which the traditional LS approximation is not accurate and for which levels of the parent ion are not populated according to their statistical weights.

In the OII 4f-3d transition array, for example, the strongest line ($\lambda4089\AA$) originates from recombination on the $O^{2+}(^3P_2)$ level. In all recombination theory to date, this level is assumed to carry 5/9 of the population of the ^3P state but at densities below $\sim$5000 cm^{-3} its fractional population may be much less. Abundances observed from this line will therefore be an underestimate for low density PNe or HII regions. This effect is seen clearly in the work of Tsamis et al. (2004)[1] whose measured intensities for components of the 4f-3d array differ markedly from current theory, in low density HII regions. No such problem is seen in the spectra of more dense PNe[2].

To model these transitions we:

- allow for the distribution of population in the ground levels of the parent ion, which is assumed to be Boltzmann in all current theoretical work;
- perform a full intermediate coupling treatment of the radiative capture and cascade problem.

We consider the recombination spectrum of OII,

$$O^{2+} + e^- \rightarrow O^+ + h\nu \qquad (1)$$

The Capture-Cascade Problem

We follow many of the methods used in the LS coupling treatment of OII described by Storey (1994)[3] and Liu et al. (2000)[2]. The capture cascade problem is solved in three stages.

- A n-resolved hydrogen-like problem (for all n).
- An nl-resolved hydrogen-like problem (for all n).
- A $J\pi$ resolved non-hydrogenic problem (for low n).

For the first two stages, electron and ion collisional processes are included. In the final stage, only radiative processes are considered.

The O^+ ion

In OII, the principal series is $2s^22p^2(^3P_{0,1,2})nlj[J\pi]$. Some states of the series $2s^22p^2(^1D_2)nlj[J\pi]$ and $2s^22p^2(^1S_0)nlj[J\pi]$ are also present.

As l increases, the appropriate coupling scheme changes from almost pure LS-coupling ($l = 0$) to pair-coupling ($l > 4$). In intermediate coupling all states are correctly treated.

New Atomic Data

The solution of the level population problem in stage 3 requires the calculation of bound-bound (oscillator strengths) and bound-free (photoionisation cross-sections) radiative data in intermediate coupling. These were calculated using the R-matrix method and RmaX[4] suite of codes.

Recombination coefficients are computed from the photoionisation cross-section data resolved by final state,

$$2s^22p^2(^3P_{0,1,2})nlj[J\pi] + h\nu \rightleftharpoons 2s^22p^2(^3P_{0,1,2}) + e(kl'j'[J'\pi']) \qquad (2)$$

plus the fractional populations of the ground levels of the recombining ion $O^{2+}(^3P_J)$.

Results

Figure 1 shows the distribution of populations among the three ground levels of O^{2+} as a function of electron density at electron temperature T=10000K.

Fig 2 shows the predictions from the present work, of the distribution of intensity (in red) within the $3p^4D^o$-$3s^4P^o$ multiplet of OII (multiplet V1), as a function of electron density. At high density the results approach those obtained in LS-coupling, which tacitly assumes a statistical distribution of population among the $O^{2+}(^3P_J)$ ground levels (shown in black).

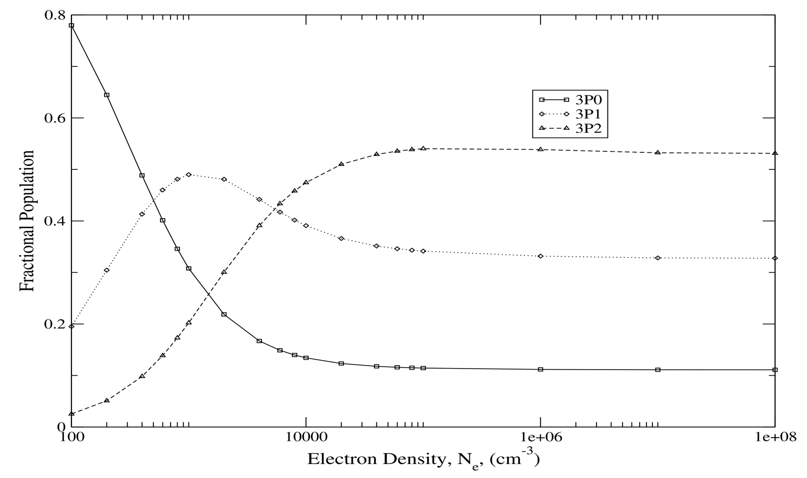

Figure 1 : Fractional populations of the O^{2+} ^3P_J levels at 10000K.

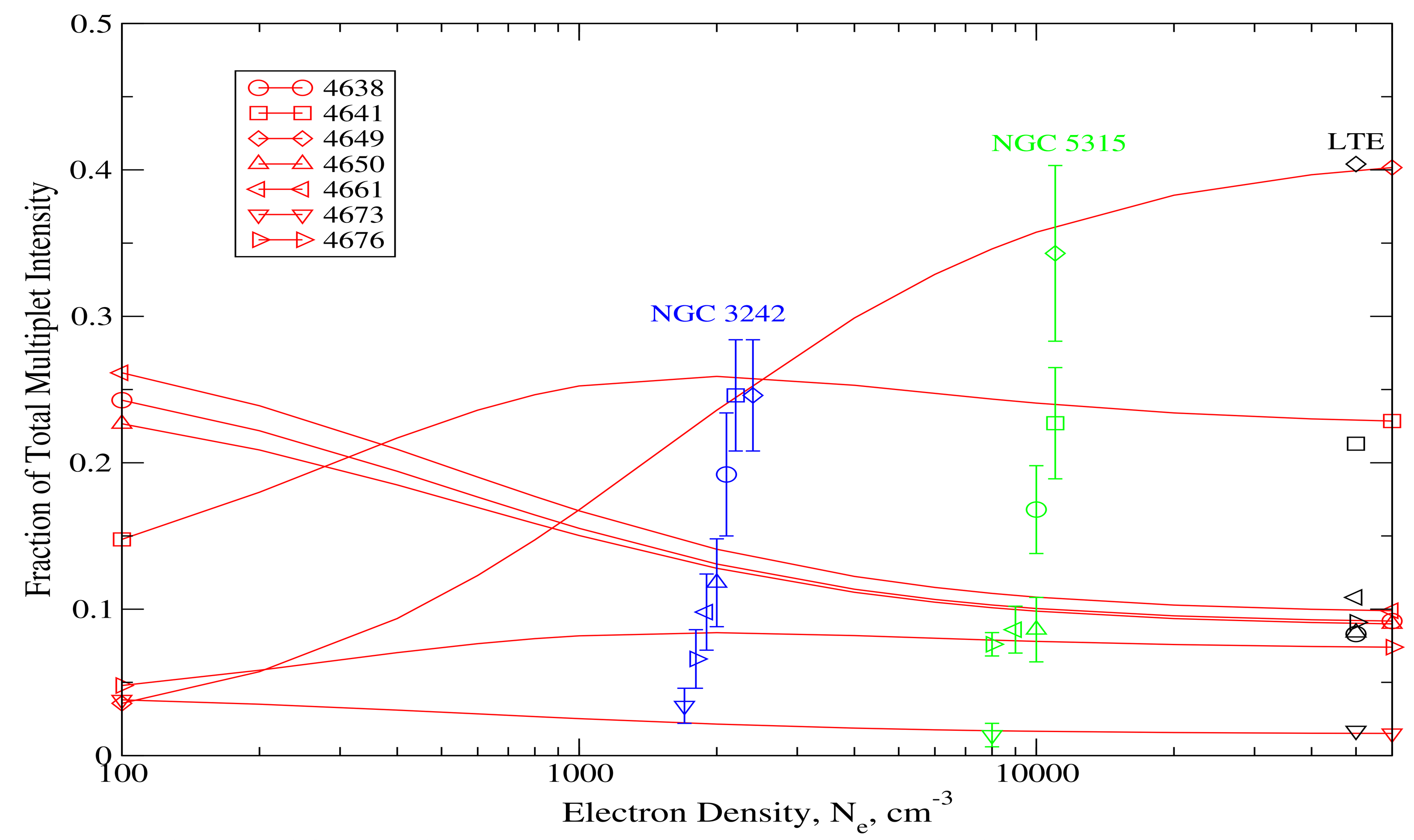

Figure 2 : Theoretical fractional intensities relative to the total V1 Multiplet intensity, with measured values for two PNe (NGC 3242 in blue; NGC 5315 in green; 2σ uncertainties) and LTE theoretical values (in black).

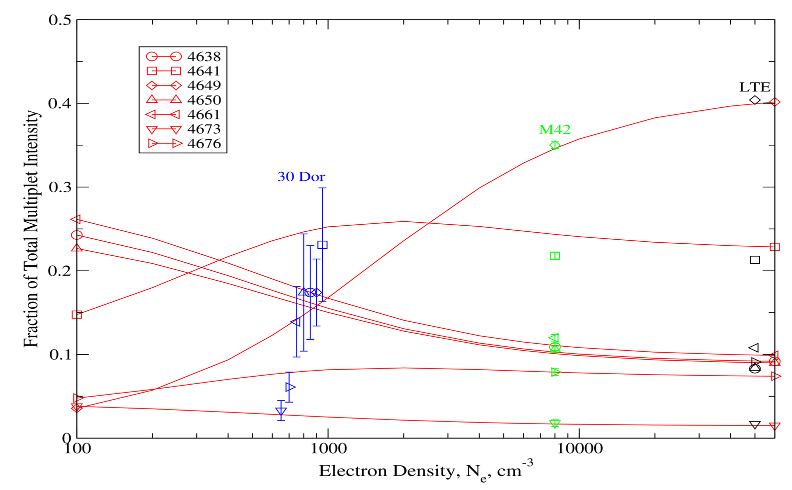

Figure 3 : Theoretical fractional intensities of OII multiplet V1 with measured values for two HII regions (30 Dor in blue; M42 in green).

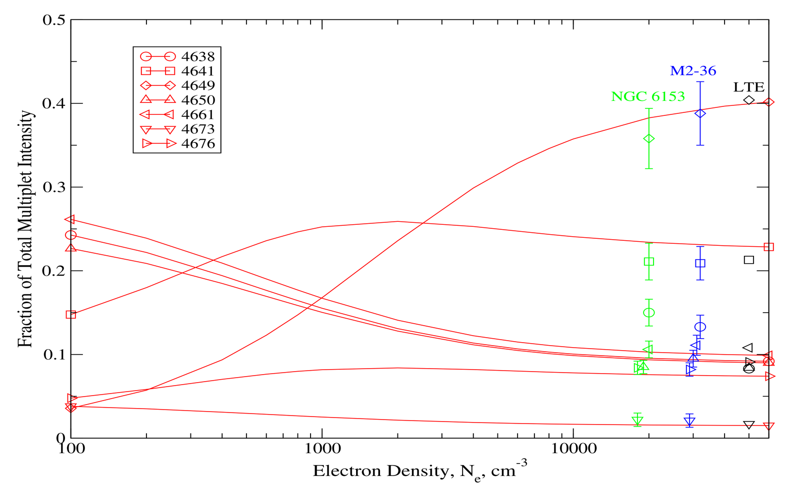

Figure 4 : Theoretical fractional intensities of OII multiplet V1 with measured values for two PNe (M2-36 in blue; NGC 6153 in green).

The strongest transition in the high density limit ($\lambda4649$) has the $O^{2+}(^3P_2)$ level as parent and therefore its intensity falls sharply as the density, and hence the $O^{2+}(^3P_2)$ population, falls. Also shown in Fig 2 are the observed fractional intensities, from Tsamis et al[1], for two PNe, plotted at the densities derived by them, 2000 cm^{-3} for NGC 3242 and 10000 cm^{-3} for NGC 5315.

In Fig 3, we show the observed ratios for 30 Dor[5] and M42[6]. Tsamis et al.[5] quote an electron density between 370 and 1800 cm^{-3} for 30 Dor. A good match to theory is obtained for a density of 800 cm^{-3}. Esteban et al.[7] quote an electron density between 2000 and 40000 cm^{-3} for M42. A good match to theory is 8000 cm^{-3}.

In Fig 4, we show the observed ratios for NGC 6153[2] and M2-36[8]. Both PNe appear close to LTE in the OII emitting regions. For NGC 6153, a good match to theory is obtained for a density of 11000 cm^{-3} (compared to 2000 cm^{-3} from forbidden lines[2]) . For M2-36, 12000 cm^{-3} provides a good match (compared to 4200 cm^{-3} from forbidden lines[8]).

$\lambda(\AA)$	NGC 3242		NGC 5315		LTE
	Obs	B&S	Obs	B&S	
4638	0.78	0.56	0.49	0.28	0.21
4641	1.00	1.10	0.66	0.67	0.53
4649	1.00	1.00	1.00	1.00	1.00
4650	0.48	0.54	0.25	0.28	0.21
4661	0.40	0.60	0.25	0.30	0.27
4673	0.14	0.09	0.04	0.04	0.04
4676	0.27	0.36	0.22	0.22	0.23

Table 1 : Relative intensities of components of OII multiplet V1, normalised to $\lambda4649$, for NGC 3242 and NGC 5315. Results for the present work (B&S, 2000 cm^{-3} for NGC 3242, 10000 cm^{-3} for NGC 5315) and in LTE are shown.

The agreement between observation and theory is good, with the exception of $\lambda4638$ which is significantly discrepant in some cases. Table 1 shows the relative intensities of the V1 components in numerical form, normalised to the $\lambda4649$ intensity.

Conclusions

We have shown that a full intermediate coupling treatment of O^{2+}+e^- recombination yields line intensity ratios in much better agreement with observation than previous work, especially for nebulae with densities below 10000/cm^3. Elemental abundances derived from the new theory will therefore be more accurate and more consistent. In addition, the new theory provides a new means of determining the electron density of the emitting region. This method is essentially equivalent to measuring electron density from ratios of infra-red fine structure lines but can be carried out with ground-based observations.

References : 1) Y. G. Tsamis et al., MNRAS, 353, 953-979, 2004, 2) X. W. Liu et al., MNRAS, 312, 585-628, 2000, 3) P. J. Storey, A&A, 282, 999-1013, 1994, 4) K. A. Berrington, P. G. Burke et al., J.Phys.B v20 pp6379-97, 1987 http://amdpp.phys.strath.ac.uk/UK_RmaX/, 5) Y. G. Tsamis et al., MNRAS, 338, 687-710, 2003, 6) J. A. Baldwin et al., AJSS, 129, 229-246, 2000, 7) C. Esteban et al., A&A, 342, L37, 1999, 8) X. W. Liu et al., MNRAS, 327, 141-168, 2001

UCL
EPSRC Engineering and Physical Sciences Research Council