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The excitation of the triplet lines of O^{2+} in nebulae

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Summary. The excitation of the triplet lines of O^{2+} between 280 and 380 nm in nebulae is attributed to a combination of the Bowen fluorescence mechanism pumped by the He^+ resonance line and charge transfer into excited states of O^{2+} in collisions of O^{3+} with neutral hydrogen atoms. The lines at 377.4 and 375.7 nm are due almost entirely to charge transfer population of the $(2p\,3p)\,^3D_1$ level. The close agreement obtained between the calculated and observed line intensities confirms the accuracy of the charge transfer rate coefficients.

1 Introduction

Triplet lines of O^{2+} between 280 and 380 nm are prominent features of the spectra of a wide range of astronomical objects. The excitation of the emission lines is usually attributed to the Bowen fluorescence mechanism in which the He^+ resonance line at 30.378 nm is absorbed into the $(2p\,3d)\,^3P_2^0$ level of O^{2+} in a transition from the $(2p^2)\,^3P_2$ level of the ground state with which it is in near coincidence at a wavelength of 30.380 nm (*cf.* Kallman & McCray 1980). Saraph & Seaton (1980) have presented a detailed analysis of the emission spectrum of the planetary nebula NGC 7662 and have shown that with the exception of the $(2p\,3p)\ ^3D-(2p\,3s)\,^3P^0$ lines at 377.4 and 375.7 nm the Bowen fluorescence mechanism explains satisfactorily the measured line intensities. They commented that other processes may contribute to the excitation of the $^3D-{}^3P^0$ multiplet.

The lines at 377.4 and 375.7 nm are emitted from the $(2p\,3p)\,^3D_1$ level. We argue here that the excitation of the $(2p\,3p)\,^3D_1$ level occurs predominantly through the charge transfer process

$$O^{3+} + H \rightarrow O^{2+}(2p\,3p\,^3D_1) + H^+.$$

We calculate the contribution of the Bowen fluorescence and charge transfer mechanisms to the excitation of the O^{2+} triplet line emissions in several nebulae observed by Aller & Czyzak (1979) and show that the two mechanisms together provide a consistent description of the measured individual line intensities.

2 Theory

Fig. 1 illustrates the emission lines produced by cascading to the $(2p\ 3s)\ ^3P^0$ state in allowed transitions from the $(2p\ 3d)\ ^3P_2^0$ state after its population by absorption of the He$^+$ resonance line. The lines are labelled by the wavelengths in nm and the spontaneous emission transition probabilities, derived from the atomic data of Saraph & Seaton (1980), and from the branching ratios listed in Allen (1963). According to the calculations of Dalgarno, Heil & Butler (1981) charge transfer of O^{3+} with H populates the $(2p\,3p)\ ^3S$ and $(2p\,3p)\ ^3D$ states but not the $(2p\,3d)\ ^3P^0$ or $(2p\,3p)\ ^3P$ states. The lines at 344.4, 342.9 and 313.2 nm and the triplet at 283.7, 282.0 and 280.9 nm originating in the $(2p\ 3d)^3P_2^0$ level and the array between 302.3 and 305.9 nm originating in the $(2p\ 3p)\ ^3P$ levels are unaffected by charge transfer and the intensity of any one of them is a direct measure of the effectiveness of the Bowen pumping mechanism. Their relative intensities depend only upon the spontaneous emission transition probabilities. It is convenient to adopt as the standard the line at 313.3 nm arising in the $(2p\,3p)\ ^3S_1 - (2p\,3d)\ ^3P_2^0$ transition.

The other triplet lines are affected both by the Bowen mechanism and the charge transfer mechanism. An independent measure of the effectiveness of charge transfer can be obtained from the singlet spectrum of O^{2+} to which pumping makes no contribution. Charge transfer into the $(2p\,3p)\ ^1P$ state is followed by emission of a photon at 559.2 nm (Dalgarno, Heil & Butler 1981). Its intensity $I(559.2)$ is given by the integral of

$$i(559.2) = 0.225 n_{\mathrm{H}} n_+ k(^1P) h\nu$$

through the nebula (Dalgarno & Sternberg 1982) where n_{H} is the density of neutral hydrogen atoms, n_+ is the density of O^{3+} ions, ν is the transition frequency and $k(^1P)$ is the rate coefficient for charge transfer into the $(2p\,3p)^1P$ state of O^{2+}.

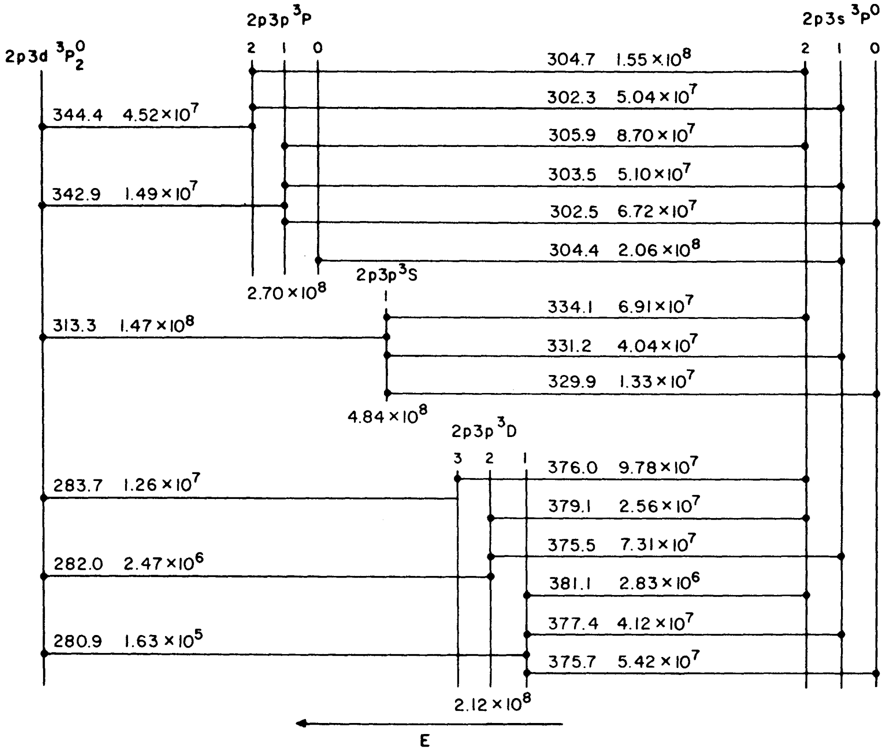

Figure 1. The triplet cascade in O^{2+}. The transitions are labelled by the participating states ^3L_J, by the wavelength in nm and by the value of the spontaneous emission transition probabilities in s. The numbers attached to each state are the total transition probabilities for emission in all possible radiative decay modes. Thus the $(2p\ 3p)^3P$ state has a radiative lifetime of $(1/2.70\times10^8)$ s.

The intensity $I(\lambda)$ of a triplet transition from the level ${}^3L_J$ which is populated by both mechanisms to the level ${}^3L_{J'}$ at a wavelength λ in nm is related to the intensities of the lines at 313.3 and 559.2 nm by the expression

$$I(\lambda) = I_b(\lambda) + I_c(\lambda)$$

where $I_b(\lambda)$ is the contribution from the Bowen mechanism,

$$I_b(\lambda) = \frac{A({}^3P_2^0 - {}^3L_J)A({}^3L_J - {}^3L'_{J'})}{A({}^3P_2^0 - {}^3S_1)\sum\limits_{L',J'} A({}^3L_J - {}^3L'_{J'})} I(313.3)\frac{313.3}{\lambda}$$

and $I_c(\lambda)$ is the contribution from the charge transfer mechanism,

$$I_c(\lambda) = \frac{k({}^3L_J)A({}^3L_J - {}^3L'_{J'})}{0.225k({}^1P)\sum\limits_{L',J'} A({}^3L_J - {}^3L'_{J'})} I(559.2)\frac{559.2}{\lambda}$$

where $A({}^3L_J - {}^3L'_{J'})$ is the spontaneous emission transition probability and $k({}^3L_J)$ is the rate coefficient for charge transfer into the ${}^3L_J$ level of O^{2+}.

3 Comparison with observations

Optical observations of NGC 7662 have been carried out by Aller, Kaler & Bowen (1966) and ultraviolet observations by Harrington, Lutz & Seaton (see Saraph & Seaton 1980), Benvenuti & Perinotto (1981) and Peña & Torres-Peimbert (1981). We adopt the triplet line intensities recommended by Saraph & Seaton (1980). Their values are listed in Table 1 in the form of intensity ratios, scaled to an intensity of 159 for $I(313.3)$. For the intensity $I(559.2)$ of the singlet line we adopt the measurements of Aller & Czysak (1979) which yield a value of 1.12×10^{-3} for $I(559.2)/I(313.3)$.

The contributions $I_b(\lambda)$ from the Bowen mechanism have been calculated by Saraph & Seaton (1980) and they are reproduced in Table 1. They show satisfactory agreement for the lines originating in the ${}^3S_1$ level and the ${}^3D_3$ and ${}^3D_2$ levels but the weaker ${}^3D_1$ lines are underestimated by an order of magnitude.

To calculate $I_c(\lambda)$ for the lines at 329.9, 331.2 and 334.1 nm originating in the ${}^3S_1$ level we use the ratio $k({}^3S_1)/k({}^1P) = 0.79$, calculated by Dalgarno *et al.* (1981) for a temperature of 10 000 K. The resulting contributions are included in Table 1. They are small and do not disturb the agreement between the measured intensities and those derived from the Bowen mechanism.

The rate coefficients for charge transfer into the individual fine-structure levels of the $(2p\ 3p)^3D$ state are not available. Transitions between ${}^3\Sigma$ and ${}^3\Pi$ molecular states formed

Table 1. Intensities $I(\lambda)$ for the triplet transitions $(2p\ 3p)^3S_1 - (2p\ 3s)\ ^3P^0$ and $(2p\ 3p)^3D - (2p\ 3s)^3P^0$ of O^{2+} in NGC 7662. The intensities used for the reference lines are $I(313.3) = 159$ and $I(559.2) = 0.18$.

		Measured I	I_b	I_c	$I_b + I_c$
${}^3S$	329.9	9 ± 2	4	0.03	4
	331.2	12 ± 3	13	0.09	13
	334.1	22 ± 5	22	0.15	22
${}^3D$	376.0	7 ± 2	5.9	0.8	6.7
	375.5	2 ± 1	0.8	0.6	1.4
	377.4	0.4 ± 0.2	0.03	0.34	0.37
	375.7	0.8 ± 0.4	0.04	0.44	0.48

Table 2. Intensities $I(\lambda)$ for the triplet transitions $(2p\,3p)\,^3S_1 - (2p\,3s)\,^3P^0$ and $(2p\,3p)\,^3D - (2p\,3s)\,^3P^0$ of O^{2+} in PK 86 – 8° 1. The intensities used for the reference lines are $I(313.3) = 66$ and $I(559.2) = 0.07$.

		Measured I	I_b	I_c	$I_b + I_c$
^3S	329.9	2	1.8	0.01	1.8
	331.2	5	5.2	0.04	5.2
	334.1	7	8.8	0.06	8.8
^3D	376.0	3	2.2	0.3	2.5
	375.5	0.8	0.4	0.25	0.65
	377.4	0.2	0.02	0.14	0.16
	375.7	0.2	0.08	0.19	0.27

by charge transfer tend to equalize the fine-structure populations as the systems separate. If we assume uniform population occurs, the value of $k(^3D_J)$ calculated by Dalgarno *et al.* (1981) leads at 10 000 K to the ratio $k(^3D_J)/k(^1P) = 1.48$. The corresponding charge transfer contributions $I_c(\lambda)$ are listed in Table 1. The inclusion of charge transfer gives a modest improvement in the agreement between theory and measurement for the intensities of the line at 376.0 nm originating in the $^3D_3$ level and the line at 375.5 nm originating in the $^3D_2$ level for which the predicted charge transfer contributions are smaller than $I_b(\lambda)$. For the lines at 377.4 and 375.7 nm from the $^3D_1$ level, to which the Bowen mechanism makes only a weak contribution, charge transfer dominates the excitation and its inclusion removes the order of magnitude discrepancy between theory and measurement.

Table 2 presents a similar comparison for PK 86 – 8° 1 derived from the observations of Aller & Czyzak (1979). We have taken the intensity $I(313.3)$ to be twice the value listed by Aller & Czyzak (1979) in order to achieve consistency between the measured intensities of the ^3S lines to which charge transfer makes a small contribution, and the predicted intensities derived from the 313.3 nm reference line. Using the doubled intensity for the 313.3 nm line yields a value of 1.1×10^{-3} for the intensity ratio $I(559.2)/I(313.3)$. As for NGC 7662, the inclusion of charge transfer has brought the predicted intensities of the $^3D_1$ lines at 377.4 and 375.7 nm into agreement with observations.

We have examined other nebulae in the compilation of Aller & Czyzak (1979), all of which reinforce the conclusion that charge transfer of O^{3+} with H is the major source of excitation of the lines emitted from the $(2p\,3p)\,^3D_1$ level of O^{2+}. The quantitative agreement between theory and observations appears to establish the accuracy of the ratio of the adopted rate coefficients for charge transfer into the $(2p\,3p)\,^1P$ and $(2p\,3p)\,^3D_1$ states of O^{2+}.

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